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AICE* SURVEY OF USSR AIR POLLUTION LITERATURE

Volume XVI

SOME BASIC PROPERTIES OF ASH AND INDUSTRIAL DUST IN RELATION TO THE PROBLEM OF PURIFICATION OF STACK GASES

Edited By

M. Y. Nuttonson

The material presented here is part of a survey of
USSR literature on air pollution
conducted by the Air Pollution Section
AMERICAN INSTITUTE OF CROP ECOLOGY

This survey is being conducted under GRANT R 800878
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OFFICE OF AIR PROGRAMS
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PREFACE

The objective of the authors of the source book* of the translated papers presented in this volume was to consolidate much of the basic information relevant to problems encountered in the field of purification of stack gases. This information, which is intended mainly for engineers and technicians concerned with problems of removal of ash and dust from gas-air discharges, may also be useful to certain scientific investigations.

The book deals with the basic properties of industrial dusts and ash from various types of fuel. It describes the most common designs of units for trapping ash and industrial dusts and methods of designing them and of calculating the technical and economic indices. It provides recommendations for a rational selection of dust removal systems as a function of the parameters of the dust-charged medium, the requirements for the degree of purification, and a number of other considerations. It also presents necessary information on the construction and calculation of gas conduits, heat insulation coatings, selection of drafting and blowing machines, and other auxiliary equipment. The main aspects of the operation of gas purification units are discussed. A separate chapter is devoted to the operational control and testing of gas purification units.

From this book we have translated the chapters dealing with:

(a) general problems related to the planning and operation of gas purification systems,

(b) principles of planning gas purification systems,

(c) determination of the basic properties of dusts and gases.

Chapters dealing with the description, illustration, and schematic presentation of the different Russian mechanical devices with Russian specifications of the models have not been included in these translations.

It is hoped that the papers selected for presentation in this volume will be conducive to a better appreciation of some of the air pollution investigations conducted in the USSR. As the editor of this volume I wish to thank my co-workers in the Air Pollution Section of the Institute for their valuable assistance.

M. Y. Nuttonson

August 1972

*Ochistka Dymovykh Gazov v Promyshlennoy Energetike. (Purification of Stack Gases in the Power Industry.) A. A. Rusanov, I. I. Urbakh, and A. P. Anastasiadi. Energiya, Moskva, 454 pages, (1969).

THE GENERAL ASPECTS OF THE DESIGN AND OPERATION OF GAS PURIFICATION SYSTEMS

A. A. Rusanov

From "Ochistka dymovykh gazov v promyshlennoy energetike". A. A. Rusanov, I. I. Urbakh, and A. P. Anastasiadi. "Energiya", Moskva, p. 5-38, (1969).

1*-1. Basic Properties of Ash and Industrial Dust

The reliability and efficiency of gas purification systems depends considerably on the physicochemical properties of the ash or dust being trapped. These properties should be thoroughly studied and taken into account in designing gas purification systems as well as organizing their operation.

The most important characteristics of ash or dust are the adhesiveness, density, abrasiveness, dispersity, chemical composition, and electrical resistivity.

1. Agglomerating Capacity

The influence of the physicochemical properties is manifested primarily in the diverse capacity of ash or dust to agglomerate and adhere to the walls of gas purification equipment and gas conduits. This property of ash or dust greatly affects the reliability of gas-purifying units; one of the most common troubles with gas-purifying equipment is their partial or total obstruction with ash or dust.

An arbitrary classification of certain types of industrial dusts into four groups according to their agglomerating capacity is given in Table 1-1. As is evident from this table, the adhesiveness of the dust depends not only on the properties of the material constituting it but also on some other factors such as moisture content, temperature, presence of nonagglomerating inclusions (particles of unburned fuel), and particle size.

The agglomerating effect is closely related to another characteristic of dust, its friability. The latter is estimated from the angle of rest, which assumes the dust to be in a freshly poured state. This quantity largely determines the behavior of dust in the hoppers and chutes of ash- and dust-catching units, the wall steepness of which is selected as a function of the friability of the particles being trapped.

Like the agglomerating capacity, the friability depends on the natural properties of dust, the size and shape of the particles, the moisture content, etc.

*Editor's note: The first digit represents chapter numbers.

The angles of rest and coefficients of friction for dust are given in Table 1-2.

Table 1-1

Agglomerating Capacity of Various Dusts.

Group I	Group II
Nonagglomerating Dusts	Slightly Agglomerating Dusts
1. Clay dust 2. Slag dust	1. Fly ash with 30% of incompletely burned material in powdered-coal combustion 2. Fly ash from fuel-bed firing of any coals 3. Coke dust 4. Magnesite dust (which has not adsorbed moisture) 5. Shale ash 6. Blast furnace dust (after primary dust precipitators) 7. Dry apatite dust
Group III	**Group IV**
Medium-Agglomerating Dusts	Strongly Agglomerating Dusts
1. Fly ash without incompletely burned material (ash from Moscow coal) 2. Peat ash 3. Manganese dust (which has adsorbed moisture) 4. Dust of nonferrous metallurgical concentrates and iron pyrite 5. Oxides of zinc, lead, tin (precoagulated)	1. Cement dust deposited from air with a high moisture content 2. Gypsum and alabaster dust 3. Dust of clay, kaolin and marls (fine) 4. Cinder dust at 500°C 5. Flour dust 6. Fiber dusts (asbestos, cotton, wool, etc.) 7. Dust containing coarse admixtures (after sifting grain, etc.) 8. Ash of anthracite culm with less than 25% of incompletely burned component

Table 1-2

Angles of Rest and Coefficients of Friction for Ash (Averaged Data).

Angle of Rest, deg		Coefficient of Friction Against Steel		Coefficient of Friction Against Concrete	
In Motion	At Rest	In Motion	At Rest	In Motion	At Rest
40	50	0,47	0,84	0,84	1,00

In regard to the properties of ash friability, it may be noted that ash trapped after slag-tap furnaces is the most friable (owing to the fused, rounded shape of its particles) and in the dry form does not usually remain suspended in the chutes and hoppers. An exception is ASh ash, which has a tendency to agglomerate.

When moist, ash loses its property of friability, and in some cases, when its content of binders is high, it acquires a setting tendency.

It should be noted that such properties of dusts as agglomeration and adhesiveness have been inadequately studied and applied to the solution of practical problems. An analysis, treatment and classification of disconnected and sometimes contradictory data on these properties are given in a monograph by A. D. Zimon [84]. This work also gives some practical recommendations for controlling the agglomeration and adhesiveness of industrial dusts.

At the time the book went to press, the NIIOGAZ (State Scientific Research Institute of Gas Purification for Industry and Sanitation) developed a procedure for determining the agglomerating capacity from the tensile strength of a layer formed as a result of filtration by placing the instrument inside the gas conduit, and began a classification of industrial dusts and ash from various types of fuel on the basis of this characteristic.

2. Density

The most important characteristic of ash and dust is their density, measured in kilograms per cubic meter or grams per cubic centimeter. The true density (characterizing the material from which the dust is obtained), bulk density and apparent density are distinguished.

The bulk density of dust, in contrast to its true density, takes into account the presence of air gaps between the particles of freshly poured dust. The bulk density is used for the determination of the volume occupied by the dust in hoppers. As the particle size uniformity increases, the bulk density

of dust decreases, since there is an increase in the relative volume of the air spaces.

Of major importance from the standpoint of dust collection is the concept of apparent density, which refers to the ratio of the mass of the particle to the volume it occupies, including pores, empty spaces, irregularities, etc. A smooth monolithic particle has an apparent density which practically coincides with the true density. In dry inertial units such particles are collected better than porous ones, since, for the same mass, they are subjected to a smaller entraining action of the purified gases leaving the gas-purifying apparatus. Conversely, particles of lower apparent density but of the same mass are more efficiently collected in such gas-cleaning equipment as foam units and bag filters, owing to the higher probability of trapping of the particles by water or by the filter cloth.

The apparent density of ash depends on its composition and may range from fractions of a gram for ash particles containing gas bubbles and inflated, porous particles of incompletely burned material, to several grams per cm^3 for ash containing particles of iron produced by reduction of the oxides entering into the composition of the mineral component of the fuel.

For comparison, Table 1-3 lists the apparent and bulk densities of ash from some types of fuel.

Table 1-3

Apparent and Bulk Densities of Ash From Some Types of Fuel

Fuel	Apparent Density, g/cm^3	Bulk Density, g/cm^3
Anthracite	2,0--2,2	0,5—0,7
Moscow coal	2,2—2,4	0,8—1,1
Vorkuta coal	1,8—2,0	0,6—0,7
Donets coal	1,9—2,5	0,4—0,7
Kuznetsk coal	2,3—2,5	—
Aleksandrovskiy coal	2,3—2,4	—
Leninskiy, Tkvarcheli coals	2,4- 2,9	—
Shales	1,8—2,1	1,0—1,1

3. Abrasiveness

In designing and operating gas purification systems it is necessary to consider the abrasiveness of ash and dust, which ranges over fairly wide limits. The rate of metal wear at the same velocities and concentrations of ash or dust particles depends on their hardness, shape, size, and weight. The wearing effect of ash or dust is usually considered in selecting the velocities of dust-laden gas streams, the thickness of the metal from which the gas conduits and gas purifying units are made, or in selecting the lining materials for them.

4. Dispersity

The behavior of particles of different sizes in dust collecting units is different, and therefore it is important to study the quantitative size distribution of the particles, or in other words, the particle size composition of ash or dust.

The particles of most industrial dusts have an irregular shape, frequently that of fragments, or irregular polyhedra. Only in some isolated cases are the dust particles spherical, particularly when produced by vapor condensation (sublimation) or when fused at high temperatures.

Particles formed as a result of a technological process (which are usually called primary) coagulate as they move along the gas conduits, forming larger (so-called secondary) particles. The latter have a very loose structure, since the primary particles are packed in such a way that the empty spaces between them occupy a much larger volume than the particles themselves.

For particles of irregular shape and particularly aggregated particles, the relationship between the sizes and the various properties (in particular, inertial properties) determining their behavior in dust-collecting units is very complex.

The inertial properties of particles are customarily evaluated from their behavior in a gravity field, namely, their sedimentation rate. To this end, the concept of the Stokes particle diameter has been introduced. The Stokes diameter of any particle, including an aggregated particle, is the diameter of a spherical particle having the same sedimentation rate as a given non-spherical particle or aggregate.

The particle size composition of ash or dust is determined experimentally. Some methods and instruments for the experimental determination of the dispersity of dusts permit the determination of the actual dimensions of the particles, while others measure their Stokes diameters.

The gravimetric portion of dust in a certain range of sizes is called a fraction. By studying the particle sizes one can compile a table of the fractional composition of a dust.

One can also compile a table which will show what fraction of the dust is made up of particles larger than a certain size. Examples of such tables are Tables 1-4 and 1-5, which list the characteristics of fly ash formed under different conditions of combustion of some types of fuel.

Graphically, the distribution of particles according to size may be represented in several ways.

Table 1-4

Characteristics of Fly Ash (According to the Data of NIIOGAZ).

Method of Combustion and Milling	Fuel	Fractional Composition of Ash, %									Ash Density, g/cm³
		Particle Size, μm									
		0—5	5—10	10—15	15—20	20—30	30—40	40—60	60—90	90	
Bed type (mechanical grate)	Moscow coal	1,3	3,7	1,5	3,5	9,0	22,0	37,0	22,0	—	2,3
Powdered coal	Lean coal (30% incompletely burned material)	13,2	10,8	7,0	6,0	10,5	10,0	20,5	22,0	—	2,2
	Lean coal (7% incompletely burned material)	4,5	9,5	33,0	19,0	13,0	7,0	6,0	8,0	—	2,2—2,3
Bed-type (hand-furnace)	Anthracite (commercial culm)	1,4	1,6	2,5	3,5	7,0	8,0	11,0	14,0	51,0	—
	Anthracite (slab, lump, chippings, culm)	6,5	9,0	6,5	6,0	8,0	6,0	9,5	11,5	37,5	1,9—2,2
In suspension	Peat	6,2	19,8	10,0	7,0	10,0	7,0	11,0	12,0	17,0	—
In eddy-type furnace of Makar'yev's system	Shale	4,0	6,0	6,0	6,0	10,0	9,0	10,0	14,0	35,0	2,0—2,5
Powdered coal (shaft-mill furnace)	Moscow coal	5,0	15,0	12,0	11,0	16,5	10,0	12,5	5,0	12,0	—
Bed-type (hand furnace)	Idem	19,4	14,0	6,1	7,6	10,5	7,9	10,1	10,8	13,5	2,0—2,2

Table 1-5

Characteristics of Fly Ash (According to the Data of TsKTI (Central Scientific Research Institute for Boilers and Turbines) and VTI (All-Union Heat Engineering Institute).

Method of Combustion and Milling	Fuel	Total Residue, % Particle Size, μm										Ash Density, g/cm³
		>0	>5	>10	>20	>30	>40	>50	>60	>80	>100	
Powdered-coal (tumbling ball mill)	Donets lean coal	100	88	68	37	26	19	15	11	6	3	2,3—2,5
Same	Kuznetsk lean coal	100	88	69	38	29	23	18	13	8	5	2,3—2,5
"	Kemerovo coal	100	92	79	57	40	30	22	16	8	5	2,2—2,4
"	Chelyabinsk coal	100	93	82	62	46	37	30	24	13	9	2,3—2,4
Powdered coal (medium-speed mill)	Moscow coal	100	90	71	48	34	26	19	14	5	2	2,2—2,4
Same	Intinsk coal	100	93	80	53	39	30	24	19	11	8	2,2—2,5
Powdered coal (hammer mill)	Vorkuta coal	100	92	75	40	26	19	15	12	6	4	2,2—2,5
Same	Tkvarcheli coal	100	97	91	79	57	41	32	27	15	9	2,4—2,5
"	Leninskiy coal	100	96	91	75	53	38	32	26	16	12	2,4—2,9
" "	Intinsk coal	100	94	79	47	25	16	10	8	4	2	2,2—2,5
" "	Vorkuta coal	100	92	75	41	25	13	8	5	3	2	2,2—2,5
" "	Kansk coal	100	95	88	66	47	34	24	18	9	6	2,2—2,4
" "	Aleksandriyskiy coal	100	94	84	55	35	23	15	11	7	5	2,3—2,4
" "	Kashpir shale	100	95	86	65	47	34	25	16	7	5	2,5—2,7
" "	Gdov shale	100	93	90	34	19	12	9	7	4	2	2,4—2,5
Powdered coal (hammer mill)	Shredded peat	100	—	97,6	90,5	74,3	—	29,3	—	—	17	—
Powdered coal (pneumatic hammer mill)	Moscow coal (dried)	100	—	54	35	26	19	14	11	7	4	—
Powdered coal (tumbling ball mill)	" " "	100	—	54	39	32	25	19	14	6	1	—
Powdered coal (tumbling ball mill)	ASh	100	—	73	51	38	30	24	15	—	—	—
Chamber (hammer crusher)	Volga shale	100	—	88	75	64	55	50	47	—	—	—

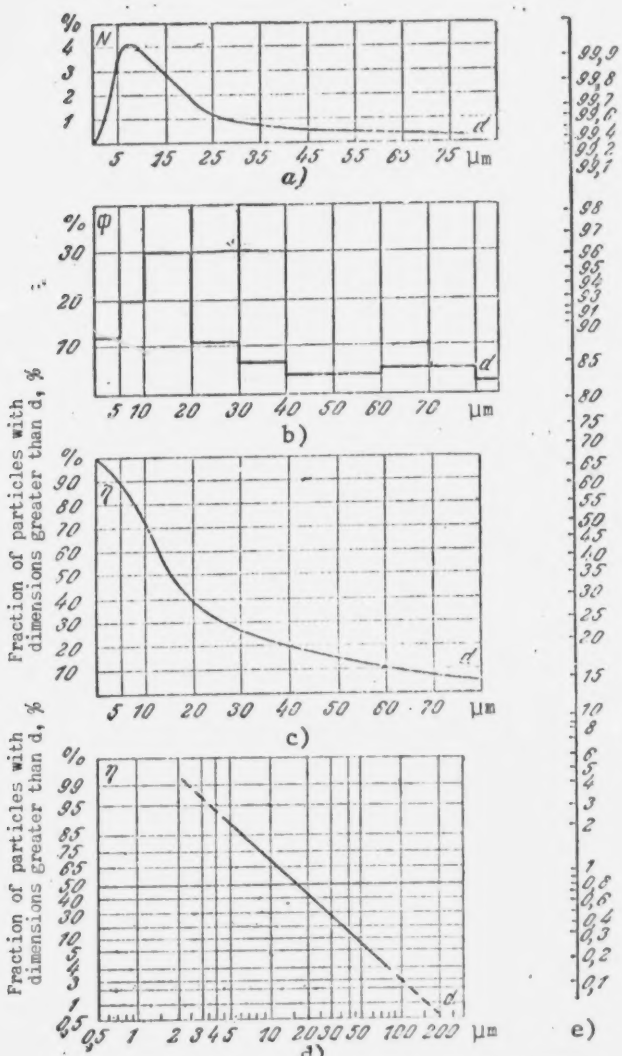

Fig. 1-1. Graphical representation of the particle size composition of ash from lean Donets coal (see Table 1-5).

a - differential distribution curve; b - fractional distribution; c - integral distribution on a linear scale of coordinates; d - integral distribution in a logarithmic probability coordinate system; e - probability scale.

A dispersity curve can be plotted by laying off the particles size along the abscissa axis on a linear scale and the fraction of particles of corresponding size along the ordinate axis. The curve obtained is called a differential curve of particle size distribution. An example of such a curve is given in Fig. 1-1 a.

If we consider that within a certain range the weight fraction of the particles is constant, a stepwise dispersity curve, i.e., a histogram, is obtained (Fig. 1-1 b).

The distribution of particles according to size is usually given in the form of integral dispersity curves. In this case, the particle size d is laid off along the abscissa axis, and the weight fraction of particles whose size is either smaller or greater than d along the ordinate axis. One can use a linear scale with coordinate axes (Fig. 1-1 c) or plot the curve in the so-called probability coordinate system (Fig. 1-1 d). The advantage of using such a coordinate system is that certain particle size distribution functions can be expressed in the form of elementary geometric curves [74].

For example, the Gauss lognormal distribution [75], which according to many studies governs many types of dust, is transformed into a straight line in the logarithmic probability coordinate system. This in turn opens up great possibilities for the interpolation and extrapolation of particle sizes.

According to the lognormal distribution (LND), the distribution of the log of particle diameters can be expressed by a probability curve (Gauss curve) whose equation in the integral form is [75]:

$$\xi\left(\frac{\ln d - \ln \bar{d}_g}{\ln \sigma}\right) = \frac{1}{\ln \sigma \sqrt{2\pi}} \int_{-\infty}^{\ln d} \exp\left[-\frac{(\ln d - \ln \bar{d}_g)^2}{2 \ln^2 \sigma}\right] d \ln d, \qquad (1\text{-}1)$$

where d is the particle diameter;

$\bar{d}_g$ is the mean geometric particle diameter;

σ is the geometric standard deviation;

$\ln^2\sigma$ is the standard deviation (dispersion) of the logarithm of the diameters from their mean value; $\xi\left(\frac{\ln d - \ln \bar{d}_g}{\ln \sigma}\right)$ is the total weight of the particles in the range d = 0-d in fractions of unity (or %), i.e., the weight content of particles less than d in diameter.

In the representation of the results of dispersity analysis in the logarithmic probability coordinates, the log of the particle diameter is laid off along the abscissa axis, and the quantity $\xi\left(\frac{\ln d - \ln \bar{d}_g}{\ln \sigma}\right)$ is laid off along

the ordinate axis on a special functional scale (quantiles).

The lognormal distribution is customarily characterized by two quantities: the geometric mean diameter and the standard deviation. When the IND is represented in logarithmic probability coordinates, i.e., in the form of a straight line, the value of $\overline{d}_g$ corresponds to the point of intersection of this line with the abscissa axis. The standard deviation is determined as the difference of the abscissas for points of the straight line with ordinates of 84.1 and 50% (or respectively 50 and 15.9%).

Knowing the parameters of a given IND, i.e., $\overline{d}_g$ and σ, one can readily trace a straight line corresponding to this distribution, which makes it possible to find the content of particles in any diameter range. Thus, the use of the logarithmic probability coordinate systen affords a means of extremely brief notation of information on the dispersity of dust obeying the lognormal distribution.

As a rule, the plotting of the straight line from parameters σ and $\overline{d}_g$ involves no difficulties, but it does become quite inconvenient in the case of distributions with high values of σ, since the abscissa axis is constructed for limited values of the diameter and the points of the straight line with ordinates of 84.1 and 15.9% may fall outside the limits of the graph. It has therefore been proposed [73] that instead of the variant σ, representing the difference of abscissas of points with fixed ordinates, another parameter should be used, namely, the value of the ordinate at an abscissa corresponding to log $2\overline{d}_g$, and that this parameter be denoted by $\xi(2\overline{d}_g)$. It should be noted that instead of the abscissa log $2\overline{d}_g$, one can take the abscissa log $\frac{\overline{d}_g}{2}$ (just as above, the ordinate 15.9% could have been taken instead of the ordinate 84.1%).

The method of plotting the straight line from the parameters log $\overline{d}_g$ and $\xi(2\overline{d}_g)$ amounts to the following. First, a point corresponding to log $\overline{d}_g$ is marked on the abscissa axis. To the right of this point, a point is then found corresponding to log $2\overline{d}_g$, and at this point a perpendicular is erected on which the quantity $\xi(2\overline{d}_g)$ or $\xi(\overline{d}_g/2)$ is laid off. The straight line is traced through the end of this perpendicular and through the point on the abscissa axis corresponding to log $\overline{d}_g$.

The advantage of using $\xi(2\overline{d}_g)$ or $\xi(\overline{d}_g/2)$ in place of σ consists, in addition to facilitating the graphical plotting of straight lines with large σ (there is no need to extend the abscissa axis), in the fact that it is no longer necessary to calculate the difference of the logs of the diameters, and there is no need for any kind of computations at all.

When these parameters are used, each LND may be briefly denoted by two numbers, the first of which (in microns) corresponds to $\overline{d}_g$, and the second

(in percent) to $\xi(2\bar{d}_g)$ or $\xi(\frac{\bar{d}_g}{2})$.

Thus, for example, the distribution characteristic of ash of Donets lean coal (see Fig. 1-4 d) may be written as follows:

$$\bar{d}_g = 16\ \mu; \quad \xi\left(\frac{d_g}{2}\right) = 25\%.$$

Considering a certain complexity in the construction of a probability scale which can hold the wide spread of the logarithmic probability coordinate system, Fig. 1-1 e gives an enlarged probability scale. The abscissa axis can be constructed by means of an ordinary slide rule.

5. Electrical Resistivity

Experience in the electrical purification of gases shows that a high electrical resistivity of a layer of ash or dust particles substantially affects the efficiency of electrostatic precipitators. The critical value of the resistivity above which the characteristics of an electrostatic precipitator decline rapidly if the layer cannot be readily shaken off the electrodes amounts to approximately 2×10^{10} ohm cm. The decrease in the efficiency of the electrostatic precipitators is associated with the appearance of a secondary brush discharge on the collecting electrodes, the neutralization of the charge on the particles in the working compartment of the apparatus, a decrease of the breakdown voltage, and also a redistribution of the working voltage between the discharge gap and the dust layer.

The electrical resistivities of a layer of particles of many types of ash and dust have values close to critical and depend on the properties of the individual particles (surface and internal conductance, size and shape of the particles) and also on the structure of the layer and parameters of the gas being purified.

The dependence of the electrical resistivity of a layer of ash or dust particles (or their conductance) on the temperature and humidity of the gas and some other factors are used in practical electrical purification of gases for a suitable pretreatment (conditioning) of the gases before they reach the electrostatic precipitators in order to improve the efficiency of the latter.

The electrical resistivity of certain types of ash is shown in Fig. 1-2.

If the electrical resistivity of the layer is under 10^3-10^4 ohm cm, the particles quickly lose their charge acquired from the discharge electrodes, then acquire the charge of the collecting electrodes. If the electrical forces arising from the newly acquired charge are sufficient to overcome the forces of adhesion, the deposited particles return to the stream of gases, thus increasing the secondary entrainment of the collected dust.

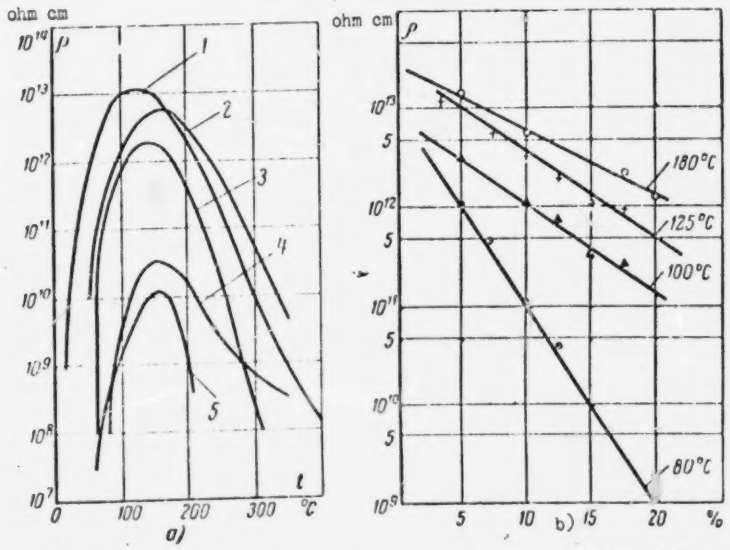

Fig. 1-2. Electrical resistivity of certain types of industrial dust and ash (data of G. M. A. Aliyev and A. Ye. Gonik).
a - dependence on temperature; b - dependence on moixture content as illustrated with ash from Moscow coal; 1 - ash from Moscow coal; 2 - lead mist; 3 - synthetic catalysts; 4 - cement dust; 5 - ash of brand ASh from Donets anthracite.

1-2. Parameters of Gases Undergoing Purification

1. Composition of Gases

Usually, the total composition of waste gases is of interest only in a study of the technological processes taking place in the fuel-burning units, and is determined by means of chemical gas analyzers based on the principle of absorption by chemical reagents or afterburning of the individual components of the gas mixture, by means of gas analyzers TsKTI, VTI-2, etc.

In dust collection processes, the only important factors are the moisture content and the content in the gases to be purified of sulfur oxides which cause an appreciable rise of the dew point t_d as compared with the condensation temperature of pure water vapor. The analysis of gases in dust-collecting practice is used mainly for the purpose of determining the magnitude of suction of external air into the dust collector. To this end, it sufficies to determine, at the entrance to the collector and at its exit, the content of any one of readily determinable components whose absolute quantity remains unchanged during passage through the dust collector, for example, CO_2 or O_2.

From the difference in the concentrations of one of the components in the gases at the entrance and exit of the dust-collecting device, one can determine the infiltration coefficient.

A calculation of the content of sulfur oxides present in the gases to be purified and formed by the combustion of various types of fuel is given in § 1-4.

2. Moisture Content

The presence of moisture in gases to be purified may cause the dust to stick and result in the corrosion of the walls of the dust collector, particularly in operation with gases at temperatures close to the temperature of precipitation of the condensate, called the dew point or t_d, °C.

The moisture content of a gas may be characterized by the following quantities:

1) Concentration of water vapor d, kg/kg of dry gas (absolute moisture content of the gas);

2) Concentration of water vapor f', g/m^3 of moist gas under standard conditions or f", g/m^3 of moist gas under actual conditions;

3) Partial pressure of water vapor p_W, n/m^2 or mm Hg;

4) Ordinary percentage, equal to $\frac{p_W}{p_{tot}} \times 100$, where p_{tot} is the total pressure of the given gas equal to the barometric pressure $B^{\pm}$ the pressure (rarefaction) p in the device;

5) The degree to which the saturated state is approached under the given conditions, i.e., the relative humidity ϕ, %.

The relative humidity is the ratio of the weight of water vapor present in 1 m^3 of moist gas to the amount of water vapor which can be contained in 1 m^3 of gas in the saturated state under the same conditions, i.e.,

$$\varphi = \frac{f''}{f''_{sat}}.$$

In calculations involving dust collection, the absolute moisture content and the relative humidity are the quantities most frequently employed.

In the solution of problems connected with the design or operation of dust collection systems, it is most important to know the dew point of the purified gases.

The dew point of flue gases formed by the combustion of low-sulfur fuels can be determined with sufficient accuracy from an I-d diagram (Fig. 1-3),

plotted for moist air if the pressure of the flue gases is close to barometric.

An I-d diagram was plotted for air at a barometric pressure of 100 kn/m^2. The enthalpy of moist air I, in kJ/kg of dry air, was laid off along the ordinate axis of the diagram.

In order to make the best use of the area of the diagram, the abscissa axis was drawn at a 135° angle to the ordinate axis. Values of the absolute humidity d, in kg/kg of dry air, were laid off along the abscissa axis. The corresponding points were projected on a horizontal (arbitrary) axis d.

The diagram shows the lines of: constant values of d running vertically; constant values I running at an angle of 135° to the ordinate axis; constant temperatures of air (gas) Θ and constant relative humidities ϕ, equal to the ratio of the partial pressure of water vapor in air to the partial pressure of vapor saturating the air at the same temperature. The temperature Θ is also called the "dry thermometer" temperature, although actually it is the temperature of the moist unsaturated gas.

The curve for ϕ = 100% is the boundary curve. The points of this curve correspond to the state of saturated air. The area under the curve ϕ = 100% is the area of wet vapor (the "fog" area).

The line of partial pressures of water vapor $p_{wv} = f(d)$ was plotted under the curve ϕ = 100%. The values of p_{wv} can be read off on the right ordinate of the diagram.

In addition, the dashed lines on the diagram represent the constant temperatures of the so-called "wet thermometer" t_w, running at a small angle to the lines I = const. In the case of saturation of the air with vapor (ϕ = 100%), a "wet thermometer" (i.e., a thermometer whose measuring end is wet) will show the same temperature as a "dry thermometer". For this reason, the isotherms on Θ and t_w for the same temperatures of the curve ϕ = 100% intersect.

The curves ϕ = const show an abrupt change at an air (gas) temperature Θ = 99.4°C, i.e., the boiling point of water corresponding to a barometric pressure of 100 kn/m^2. In the area above this temperature, the lines of Θ almost coincide with the lines of d.

The diagram relates four basic parameters: the enthalpy of moist air I, kJ/kg of dry air, its moisture content d, kg/kg of dry air, the temperature t, °C, and the relative humidity Θ, %. Knowing two of these parameters, one can determine the other two for any state of air.

In order to determine the dew point, it is necessary to trace the line d = const from the point characterizing the state of the moist gas to the

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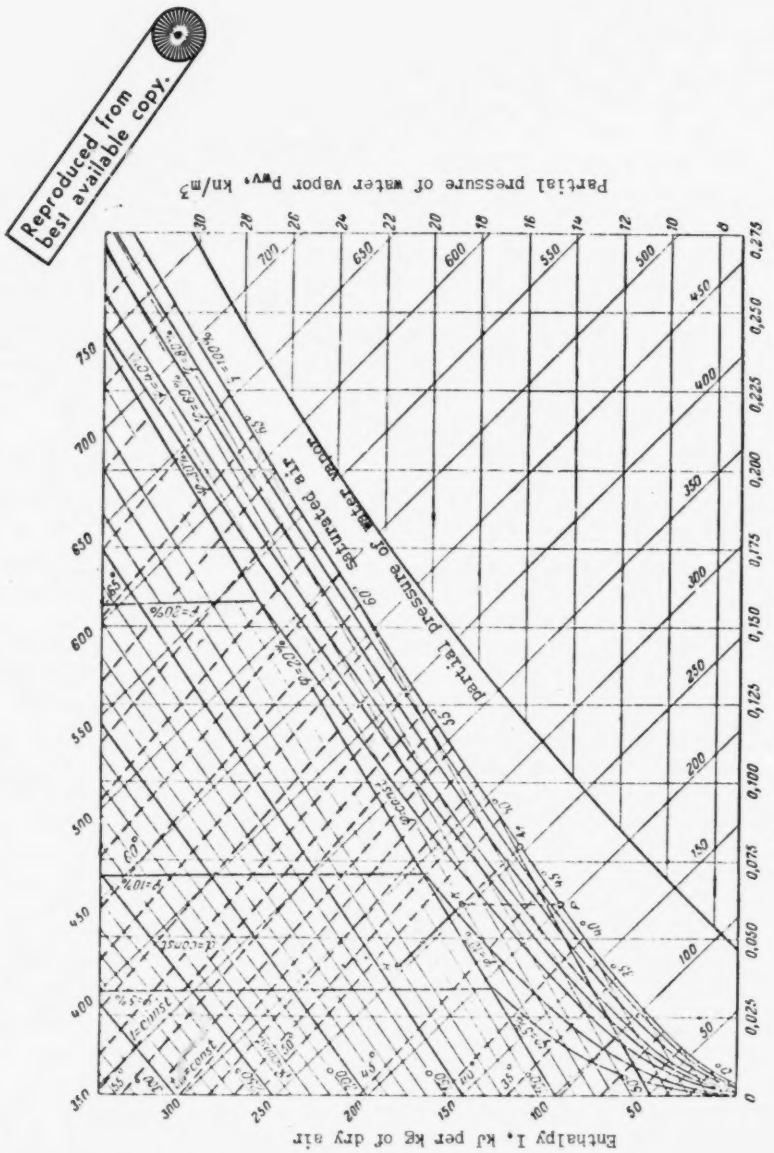
Partial pressure of water vapor p_{wv}, kn/m³
Moisture content d, kg/kg of dry air
Enthalpy I, kJ per kg of dry air
Partial pressure of water vapor
Saturated air

Fig. 1-3. I-d diagram for moist air.

intersection with the curve $\phi = 100\%$. The isotherm passing through this point will give the condensation temperature of water vapor.

The absolute moisture content of flue gases entering a gas purification system from boiler units may be calculated from the formula

$$d_g = \frac{\rho^0_{H_2O} V^{en}_{H_2O}}{1 - 0{,}01\,(A^w + W^w + 9H^w) + \rho^0_a\, \alpha^{en}_{dc} V^0}, \quad \text{kg/kg of dry gases} \tag{1-2}$$

where $V^{en}_{H_2O}$ is the volume of water vapor at standard conditions at the entrance to the dust collector, m^3/kg of fuel;

$\rho^0_{H_2O}$ and ρ^0_a are, respectively, the densities of water vapor and of dry air at standard conditions; $\rho^0_{H_2O} = 0{,}804$ kg/m^3, $\rho^0_a \approx 1{,}3$ kg/m^3;

A^w, W^w, H^w are the ash content, moisture content and hydrogen content of the working mass of fuel, %;

α^{en}_{dc} is the coefficient of excess air at the entrance to the dust collecting system.

The volume of water vapor at the entrance to the dust collector, determined after the boiler unit, is approximately equal to the theoretical volume of water vapor formed by the combustion of fuel, $V^0_{H_2O}$

$$V^0_{H_2O} = 0{,}111H^w + 0{,}0124W^w + 0{,}016V^0 + 1{,}24G_b, \text{ m}^3/\text{kg}, \tag{1-3}$$

where G_b is the amount of vapor introduced with the blow, kg/kg of fuel.

For flue gases used as the heat carrier in industrial heat-engineering installations, and gases coming in contact with moist material, the absolute moisture content must be indicated in the technical project of a dust collection system. If the specific moisture content of flue gases must be known in order to solve problems connected with the modernization or running of the dust-collecting system of an operating installation this quantity can be determined experimentally (see § 11-2).

In a fuel with a reduced sulfur content $S^{red} > 0.05\%$ per MJ/kg, sulfuric anhydride SO_3, which in small amounts is present in the gases together with sulfurous anhydride SO_2, has a substantial influence on the dew point. With water vapor, sulfuric anhydride forms a certain amount of sulfuric acid H_2SO_4,

the solution of which condenses at a higher temperature than water vapor. According to the data of the VTI, the dew point at $S^{red} > 0.05\%$ per MJ/kg may be determined with sufficient accuracy from the formula

$$t_d = t_{cond}^{H_2O} + \frac{\beta \sqrt[3]{S^{red}}}{1{,}05^{4{,}19\alpha_c} A^{red}}, \ ^\circ C, \qquad (1\text{-}4)$$

where $\beta = 195$ for excess amounts of air at the end of the furnace,
$\alpha_f = 1.2\text{-}1.25$ and $\beta = 208$ for $\alpha_f > 1.25$;
α_c is the fraction of ash in the carryover;
A^{red} and S^{red} are the reduced contents of ash and sulfur in the working mass, % per MJ/kg.

The condensation temperatures of water vapor and dew points of flue gases for certain fuels are given in Table 1-6.

At the dew point, the sulfuric acid corrosion occurs most vigorously, and when the temperature deviates from t_d in one or the other direction, the corrosion rate falls off rapidly (see for example Fig. 1-4).

However, as the temperature of the gases decreases further, condensation of water vapor on the walls of the gas conduits begins, and the corrosion rate increases somewhat, reaching a maximum at $t_{cond}^{H_2O}$ Thus, two corrosion rate maxima occur (Fig. 1-4): at t_d (higher peak) and at $t_{cond}^{H_2O}$ (lower peak).

Let us note that a partial trapping of SO_3 takes place in wet ash collectors; this may lower the dew point and bring it closer to the condensation temperature of water vapor (see § 1-4).

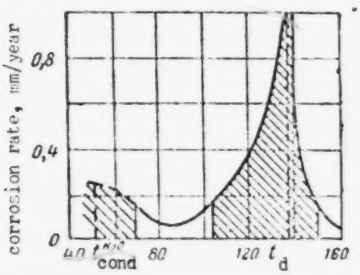

Fig. 1-4. Corrosion rate versus metal temperature for flue gases of Moscow coal (corrosion-prone areas are crosshatched).

In designing scrubbers it is necessary to determine $t_{cond}^{H_2O}$ and t_d in order to evaluate the possibility of corrosion of the gas conduits. Obviously, for wet ash collectors, the maximum of sulfuric acid corrosion can take place in the gas conduits before the ash collector. After the latter, because of the trapping of SO_3 and cooling of the gases, steps must be taken against water corrosion. The minimum permissible temperature of the gases is established by taking into account the hygroscopic properties of the collected dust. For coal and shale dust, ash and other nonhygroscopic dusts, $t_{pg} = t_d + (15\text{-}20)\ ^\circ C$[2]. For hygroscopic dusts (cement, clay, etc.), $t_{pg} = t_d + (40\text{-}50)\ ^\circ C$.

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Table 1-6

Condensation Temperature of Water Vapor and Dew Point of Flue Gases for Certain Types of Fuel (Based on VTI Data).

Fuel	Reduced Content, %/MJ/kg of			Coefficient of Excess Air in Furnace, α	Partial pressure of Saturated Water Vapor, Mn/m^2	Condensation Temperature of Water Vapor t, °C	Dew Point t_d, °C	$t_d - t$
	Sulfur S^w	Ash A^w	Moisture W^w					
Moscow coal	0,28	1,67	2,90		0,0095	44,7	142,5	97,8
Same	0,25	1,60	2,95		0,0125	51,5	142,5	91,0
. .	0,25	1,70	2,95			49,5	142,5	93,0
. .	0,27	1,63	2,95			50,3	142,5	92,2
. .	0,27	1,73	2,95		0,0100	45,9	141,0	95,1
. .	0,30	1,63	—	1,3	0,0124	50,0	145,0	95,0
Dried Moscow coal	0,28	1,52	—	1,3	0,0124	39,5	140,0	100,0
Same	0,25	2,11	1,07	1,2	0,0087	43,0	140,0	97,0
. .	0,29	2,05	1,18	1,2	0,0105	46,0	138,0	92,0
Lean Donets coal	0,09	0,435	0,15	1,2	0,0046	31,0	125	94,0
Same	0,11	0,81	0,20	1,2	0,0055	34,0	125	91,0
ASh Donets fuel	0,09	0,61	0,28	1,01—1,14	0,0050	32,0	107	75,0
Kizel coal	0,25	1,25	0,19	1,2	0,0038	38,0	138	100,0
Same	0,26	1,17	0,19	1,05—1,2	0,0038	38,0	132	94,0
Intermediate product of Kizel coal	0,53	2,27	0,34	1,25	0,0073	39,5	153	113,5
Same	0,49	1,96	0,24	1,2	0,0068	38,0	150	112,0
Mixture of Kizel coal with intermediate product	0,41	1,96	0,34	1,2	0,0038	38,0	147	109,0
Intermediate product of Donets coking coals	0,14—0,24	2,65—1,5	0,17—0,81	1,25	0,0075	40,0	117—127	77—87
Estonian shale	0,13	3,45	1,13	—	0,0100	46,0	78—81	36,0
Shredded peat	0,017	0,61	7,09	1,2	0,0244	64,0	64	0
Same	0,005	0,47	—	1,5	0,0153	54,0	63	—
Sulfur containing fuel oil	0,065	0	0,05	1,2	0,0088	43,0	120	77
Same	0,065	0	0,05	1,01—1,37	0,0095	44,0	128—142	77—93
Coke-oven gas	0,13	0	0,02	1,2	0,0103	46,0	148	102
Same	0,13	0	0,02	1,25	0,0103	46,0	152,5	106,5

3. Density

The flue gases formed by the combustion of fuel consist of several components. In carrying out measurements of dust and calculations of gases, it is necessary to know the density of the gases ρ, kg/m^3. The density of the combustion products of energy-producing types of fuel at standard conditions (temperature t = °C and barometric pressure B = 760 mm Hg) can be assumed with sufficient accuracy for the calculation to be approximately equal to the air density at the same conditions, i.e., ρ_0 = 1.3 kg/m^3.

The actual density of the combustion products (or of their mixture with air) may be obtained from the formula

$$\rho_a = \rho_0 \frac{273(B+p)}{B(273+t)}, \text{ kg/m}^3 \qquad (1\text{-}5)$$

where B is the barometric pressure, n/m^2 or mm Hg;

p is the pressure or rarefaction in the gas conduit, n/m^2 or mm Hg;

t is the gas temperature, °C;

B = 760 mm Hg $\approx$ 101 325 n/m^2.

In the presence of a high moisture content (for example, when the combustion products are used as the drying agent), the density of the flue gases may change to a value which is essential for the accuracy of the calculations being performed.

A formula is given below which permits one to determine the density of the gases if their absolute moisture content d, kg/kg of dry gas, is known:

$$\rho_{0\,mo} = \frac{1+d}{\frac{1}{\rho_0\,dr} + \frac{d}{0{,}804}}, \text{ kg/m}^3 \qquad (1\text{-}6)$$

4. Dust Contents

The dust content or concentration of dust in gases designates the weight of solid particles per m^3 of gases reduced to standard conditions.

The dust content is measured in milligrams or grams per m^3.*

Calculations for the determination of the dust content of gases are given in § 1-3. The methods of experimental determination of the gas content in gas

* In evaluating the biological harmfulness of discharges into the atmosphere, use is also made of the concept of countable concentration, which designates the number of particles per unit volume, but this quantity usually is not employed in dust collection practice.

conduits of operating boiler units and industrial heat engineering equipment are described in Chapter 10.

1-3. Discharge of Flue Gases, Their Density, and Their Ash or Dust Concentration

The amount of flue gases leaving a boiler unit or industrial heat-engineering installation is usually indicated when a technical project of a gas purification system is issued. This is because the discharge of flue gases must be calculated ahead of time, in the course of planning of the basic processing equipment after which the gas purification system must be installed.

If for one reason or another the discharge of flue gases must be specially computed in the course of planning of the gas purification system, this can be done by using the formulas given in the present section.

1. Excess air coefficient in flue gases at the entrance to the dust collector.

$$\alpha_{dc}^{en} = \alpha_{esc} + \Delta\alpha_g, \tag{1-7}$$

where α_{esc} is the excess air coefficient in the escaping gases; after large-capacity boiler units, it may be assumed equal to 1.25-1.35, and after small and middle sized boilers, 1.5;

$\Delta\alpha_g$ are the air infiltrations in the gas conduits before the dust collector; they are assumed equal to 0.001 for every running meter of length of steel gas conduits and to 0.005 for every meter of length of brick horizontal flues.

2. Average air excess coefficient in the dust collector.

$$\alpha_{dc}^{av} = \alpha_{dc}^{en} + \frac{\Delta\alpha_{dc}}{2}, \tag{1-8}$$

where α_{dc} are the air infiltrations in the dust collector; they are assumed equal to 0.05 for cyclone ash collectors; 0.1 for electrostatic precipitators; 0.08 for centrifugal scrubbers, and 0.05 for wet-rod ash collectors.

3. Volume of combustion products at the entrance to dust collectors reduced to standard conditions per kg of fuel.

$$V_g^{en} = V_g^0 + 1{,}016\left(\alpha_{dc}^{en} - 1\right)V^0, \tag{1-9}$$

where V^o_g is the volume of combustion products for $\alpha = 1$, m^3/kg;

V^o is the theoretical volume of air necessary for the combustion of fuel, m^3/kg (for a gas, m^3/m^3.

The values of V^o_g and V^o for different types of fuel are given in Tables 1-7 and 1-8.

4. Volume of combustion products in the dust collector at standard conditions per kg of fuel:

$$V_g^{av} = V_g^{en} + 1{,}016 \frac{\Delta\alpha}{2} V^o, \ m^3/kg \qquad (1\text{-}10)$$

$$V_g^{ex} = V_g^{en} + 1{,}016 \Delta\alpha_{dc} V^o, \ m^3/kg \qquad (1\text{-}10')$$

5. Actual flow rate of gases. In calculations of the actual flow rates of gases, it is approximately assumed that the volumes of the combustion products and air change in proportion to the absolute temperature:

$$Q_g^{en} = B_c V_g^{en} \frac{273 + \phi_{esc}}{273}, \ m^3/sec \qquad (1\text{-}11)$$

$$Q_g^{ex} = B_c V_g^{ex} \frac{273 + \phi''}{273}, \ m^3/sec \qquad (1\text{-}11')$$

where B_c is the calculated discharge of fuel per boiler unit or other fuel-consuming installation, kg/sec;

θ_{esc} and θ'' are respectively the temperature of the gases escaping from the boiler unit or some other processing installation and dust collector, °C.

For dry dust collectors, $\theta'' = \theta_{esc}$ - (5-10)°C; for wet ones, see formula (3-13).

Formulas (1-10), (1-10') and (1-11') are completely valid for dry dust collectors only. For scrubbers, where vaporization of water takes place and the gas temperature falls, the formulas can be used conditionally for a preliminary selection of the type and size of dust collector.

The formulas given above apply to the case of complete fuel combustion. In fuel-consuming industrial heat-engineering units (for example, in furnaces for oxidation-free metal heating), the excess air is sometimes reduced relative to the theoretical amount required to provide a reducing atmosphere in the working compartment of the unit.

When there is a marked decrease of the excess air required for complete combustion, the calculation of the amounts of gas to be purified should be

Table 1-7

Average Characteristics of Principal Solid and Liquid Fuels [77]

Fuel	Rank	Moisture Content of Working Mass W^w, %	Ash Content of Working Mass, A^w, %	Lowest Heat of Combustion, Q^w_i, kJ/kg	Theoretical Volume of Air V^0, m³/kg	Volume of Combustion products V^0_g at $\alpha = 1$, m³/kg
A. Coals						
Donets Basin						
Long-flame gas fuel	D	13,0	19,6	20 200	5,35	5,86
Gas fuel	G	7,0	15,8	24 700	6,53	7,01
Rich boiler fuel	PZh	6,0	18,8	25 000	6,53	6,96
Lean	T	5,0	15,2	27 300	7,21	7,6
Semianthracite	PA	5,5	15,1	26 800	7,20	7,55
Fine and flaxseed anthracite	AM and AS	5,0	13,3	27 100	7,21	7,48
Raw anthracite	Arsh	6,0	16,9	25 500	6,76	7,04
Anthracite culm	Ash	7,0	16,7	25 100	6,63	6,93
Intermediate product of wet dressing	PPM	11,0	40,1	15 300	4,15	4,52
Mud	—	20,0	16,0	21 200	5,66	6,21
Kuznetsk Basin						
Anzhero-Sudzhensk	PS	6,5	12,2	28 100	7,47	7,89
Kemerovo	K-PS-SS	9,0	15,5	25 000	6,64	7,11
Same	PS-T	8,0	14,7	26 600	7,05	7,47
Leninskiy	D	10,0	5,0	26 400	6,88	7,47
Same	G	9,0	10,9	26 100	6,90	7,44
Aralichevskiy	T	7,0	16,7	25 700	6,82	7,22
Intermediate product of dry dressing	PPS	4,0	25,0	23 700	6,19	6,58
Ural						
Kizel	G	5,5	29,3	20 800	5,52	5,9
Bogoslovka	Bm	28,0	21,6	11 900	3,27	3,90
Chelyabinsk	B	17,0	24,9	15 750	4,18	4,71
Other Deposits						
Karaganda bituminous coal	PZh-PS	7,5	25,0	22 250	5,82	6,23
Karaganda brown coal	B	26,0	17,0	15 150	4,09	4,71
Ekibastuz	SS	8,0	36,8	16 950	4,51	4,90
Moscow	B	33,0	23,5	10 500	2,98	3,62
Pecherskiy	PZh	7,0	18,6	24 800	6,44	6,79
Same	D	11,0	21,9	18 150	4,82	5,29
Cheremkhovo	D	14,0	21,5	19 500	5,17	5,70
Raychikhinsk	B	37,0	9,5	12 850	3,56	4,29

Continued 1-7

Fuel	Rank	Moisture Content of Working Mass W^r, %	Ash Content of Working Mass, A^r, %	Lowest Heat of Combustion, Q^r_{χ}, kJ/kg	Theoretical Volume of Air V^0, m^3/kg	Volume of Combustion products V^0_g at $\alpha = 1$, m^3/kg
Suchan	PZh	6,0	21,6	24 000	6,29	6,72
Same	T	6,0	23,5	24 000	6,30	6,66
Artemovskiy	B	28,0	21,6	13 100	3,57	4,22
B. Other Fuels						
Estonian shale	—	15,0		11 400	2,99	3,50
Shredded peat	—	50,0	5,5	9 500	2,51	3,43
Lump peat	—	40,0	6,6	10 700	3,01	3,87
Wood	—	40,0	0,6	10 200	2,81	3,75
Coke fines	—	20,0	12,0	21 850	5,91	6,36
Low-sulfur fuel oil	—	3,0	0,3	39 000	10,28	11,06
Sulfur-bearing fuel oil	—	3,0	0,3	38 400	10,15	10,92

Table 1-8

Average Characteristics of Principal Gaseous Fuels

Name of Fuel	Lowest Heat of Combustion of Dry Gas Q^w_{χ}, kJ/m³	Theoretical Volume of Air V^0, m³/m³	Volume of Products of Complete combustion V^0_g at $\alpha = 1$, m³/m³
Blast-furnace gas (from coke)	4 000	0,78	1,61
Coke gas (clean)	16 500	3,93	4,67
Gas from petroleum refining (pyrolysis)	47 250	12,05	13,31
Natural gas:			
Ukhta	33 300	8,83	9,99
Buguruslan	34 000	9,01	10,22
Kurdyumskiy	33 600	8,94	10,09
Yelshanka (Saratov)	35 800	9,51	10,68
Melitopol'	35 100	9,34	10,49
Dashava (Western Ukraine)	35 600	9,48	10,64
Stavropol'	35 500	9,45	10,53
Shebelinskiy	35 400	9,40	10,48

carried out by using formulas or nomograms given in ref. 76 or in other literature sources.

6. Density of flue gases at the entrance to the dust collector at standard conditions

$$\rho_g^0 = \frac{1 - 0{,}01Aw + 1.306\alpha_{dc}^{en}V^0}{V_g}, \text{ kg/m}^3 \qquad (1\text{-}12)$$

where Aw is the ash content of the working mass of fuel, %.

7. Actual density of flue gases at the entrance to the dust collector.

$$\rho_g = \rho_g^0 \frac{273}{273 + \Phi_{esc}}, \text{ kg/m}^3 \qquad (1\text{-}13)$$

8. Amount of ash in the carryover, taking into account the incompletely burned material at the entrance to the dust collector

$$G_{ash}^{en} = 0{,}01Bq_{car}\left(A^w + q_4\frac{Q_{av}^w}{32{,}7}\right), \text{ kg/sec} \qquad (1\text{-}14)$$

where B is the total flow rate of fuel per second, kg/sec;

q_4 is the heat loss with the mechanical incompletely burned material (see Table 1-9), %;

Q_{av}^w is the available fuel heat, MJ/kg;

32.7 is the heat of combustion of the incompletely burned material (carbon), MJ/kg;

a_{car} is the fraction of ash (and incompletely burned material) in the carryover assumed equal to:

for pulverized-fuel-fired dry-bottom furnaces	0.9
for shaft-mill furnaces during combustion of coal	0.85
for shaft-mill furnaces during combustion of shales	0.7
for furnaces with heated slag hoppers	0.8-0.85
for wet-bottom furnaces:	
single-chamber furnaces	0.9-0.7
twin-chambered furnaces	0.4-0.5
with preliminary chambers	0.1-0.15
for furnaces with chain grates during combustion of brown and bituminous coals	0.2
for furnaces with chain grates during combustion of anthracites	0.05-0.1

9. Concentration of carryover in gases at the entrance to the dust collector.

For boiler units

$$C_{ash}^{en} = \frac{G_{ash}^{en} 10^3}{Q_g^{en}}, \ g/m^3. \qquad (1\text{-}15)$$

For fired driers and other industrial heat-engineering units

$$C_{dust}^{en} = \frac{(G_{ash}^{en} + G_{em}^{en}) 10^3}{Q_g^{en}}, \ g/m^3, \qquad (1\text{-}16)$$

where G_{em}^{en} is the amount of material processed in the fuel-operated unit and entrained by the fuel gases, kg/sec.

For drying units

$$G_{em}^{en} = G_m^{dr} - G_{col}, \qquad (1\text{-}17)$$

where G_m^{dr} is the amount of material being dried referred to the moisture content of the dry material, kg/sec, determined by weighing the material G_m^{moist} supplied for drying and finding its moisture content W^{moist}, % and the moisture content of the dry material W^{dr}, %,

$$G_m^{dr} = G_m^{moist} \frac{100 - W^{moist}}{100 - W^{dr}}, \ kg/sec;$$

G_{col} is the amount of dried material discharged from the drier and collected by the preliminary purification stages, kg/sec.

Table 1-9

Heat Loss Due to Mechanical Incompleteness of Combustion q_4, %.

Fuel	Pulverized-Coal-Fired Furnaces	Shaft-Mill Furnaces	Chain Grate Furnaces	Furnaces with Chain Grate and Fuel-Bed Stoking
AS and AM anthracite	—	—	7	—
Anthracite culm	4	4	14	—
Lean coals	2	1	—	—
Bituminous coals	2	5	6	6
Dressing waste	3	—	—	—
Brown coals	1,7	1,5	5	9
Gdov and Estonian shales	—	1,5	—	—
Shredded peat	—	1,5	—	—

1-4. Chemical Processes Occurring in Dust Collectors

In wet dust collectors (scrubbers), in addition to the process of collection of ash carryover and material processed in heat-consuming units, there also occur chemical processes of absorption of CO, CO_2, SO_2 and SO_3 from the flue gases.

This absorption takes place as a result of the solubility of the oxides in water with the formation of acids, and the reaction of the oxides (acids) with the hardness salts of the water and with the ash alkalis.

It should be noted that calcium sulfate ($CaSO_4$) formed by the reactions may cause obstruction of dust collector parts. A moderate water hardness and ash alkalinity are therefore preferred. A large amount of sulfur oxides in gases promotes corrosion of the equipment.

The concentration of alkalis in the ash can be found if one knows the total content of the alkali-forming oxides CaO, MgO and K_2O from the analysis of the fuel ash. The concentration of free alkali in the ash is then

$$\text{Alk} = C\frac{V}{M}K\cdot 10^3, \text{ mg-eq/kg}, \tag{1-18}$$

where C is the content of oxides based on the ash analysis, %;

V is the valence of oxygen, equal to 2;

M is the molecular weight;

K is a coefficient indicating the ratio of free alkalis to the total amount of oxides given by the analysis; it is approximately equal to 0.375.

For CaO, which is the main oxide of the alkali elements, $\text{Alk} \approx 134\ C_{CaO}$.

For different types of fuel, Table 1-10 gives the concentrations of alkalis in ash and the concentration of sulfur (organic and pyrite) in the working mass of fuel.

1. Efficiency of collection of sulfur oxides from flue gases. The efficiency of collection of sulfuric anhydride depends on the hardness of the spray water, alkalinity of the ash, and also solubility of SO_2 in pure water. The volume concentration of sulfurous anhydride in the flue gases, expressed in percent, is calculated from the formula

$$r_{SO_2} = \frac{V_{SO_2}}{V_g^{en}}\cdot 100 = \frac{0{,}68S^w}{V_g^{en}}, \%, \tag{1-19}$$

where S^w is the content of organic and pyrite sulfur in the working mass of fuel, %;

V_g^{en} is the volume of gases at the entrance to the ash collector at standard conditions, m^3/kg.

Table 1-10

Alkalinity and Sulfur Content of Fuels [1]

Fuel	Alk, mg-eq/kg of ash	$\frac{A^d Alk}{S^d} \times 10^{-3}$ mg-eq/kg of sulfur	S^{red}, %/MJ/kg
Estonian shale	6 800	170,0	0,093
Gdov shale	5 800	196,0	0,150
Angren coal	5 360	42,0	0,098
Kansk coal	5 020	103,3	0,031
Savel'yevskiy shale	4 260	71,5	0,483
Chernovskiy coal	3 930	58,2	0,031
Kashpir shale	3 530	44,8	0,574
Kyzyl-Kiya coal	3 070	20,0	0,107
Sulyukta coal	2 900	57,6	0,031
Bogoslovka coal	2 320	167,0	0,025
Aleksandriyskiy coal	2 150	11,7	0,375
Mukachevo coal	1 800	112,0	0,064
Karaganda coal B	1 710	48,4	0,277
Karaganda bituminous coal	1 590	49,6	0,036
Donets lean coal	1 410	7,95	0,098
Chelyabinsk coal	1 380	28,6	0,076
Novovolynsk coal	1 310	4,2	0,133
Prokop'yevsk coal	1 290	23,8	0,001
Artema coal	1 230	88,5	0,002
Minusinsk coal	1 120	19,6	0,002
Anthracite culm	1 090	10,7	0,067
Aralichevskiy coal	1 050	29,3	0,024
Pecherskiy coal D	1 040	10,4	0,014
Moscow coal B	970	7,9	0,280
Yegorshino coal A	960	50,0	0,002
Donets coal PPM	950	10,0	0,250
Cheremkhovo coal	920	19,8	0,052
Sakhalin coal B	655	32,6	0,022
Lipovets coal D	600	44,0	0,016
Tkvarcheli coal	520	9,9	0,010
Kizel coal	440	2,53	0,250
Ekibastuz coal	410	18,9	0,048

The concentration of sulfurous anhydride in the gases, expressed in milligram-equivalents and referred to 1 kg of spray water, is

$$Z_{SO_2} = r_{SO_2} \rho^0_{SO_2} \frac{1}{g} \frac{V}{M} \cdot 10^3 = 890 \frac{r_{SO_2}}{g}, \text{ mg-eq/kg} \qquad (1\text{-}20)$$

where $\rho^0_{SO_2} = 2.858$ kg/m^3 is the density of SO_2 at standard conditions;

g is the specific consumption of spray water per m^3 of gases at standard conditions, kg/m^3;

V=2 is the valence of SO_2;

M=64 is the molecular weight of SO_2.

The amount of sulfurous anhydride absorbed (Abs) from the flue gases may be approximately determined from the relation

$$Abs = Sol + H + n\,Alk', \text{ mg-eq/kg}, \qquad (1\text{-}21)$$

where Sol is the solubility of SO_2 in pure water, mg-eq/kg (Table 1-11);

H is the hardness of spray water, mg-eq/kg;

Alk' is the free alkalinity of ash reduced to 1 kg of water, mg-eq/kg;

n is the leaching coefficient; for lack of other data, it may be assumed equal to unity.

The carbonate hardness of the water spraying the scrubber depends on the sources of water supply and may vary during the course of the year. Average data on the carbonate hardness of water of several sources are (in mg-eq/kg): Volga - 2; Moscow River - 1.5-5.7; Ural River - 2.2-5.7; Don River - 2; Severnyy Donets River - 8.37; Neva River - 0.56; Black, Caspian and Aral Seas~67.

Table 1-11

Solubility of Sulfurous Anhydride in Water (mg-eq/kg).

SO_2 Content of Flue Gases, %	Water Temperature, °C.				
	40	45	50	55	60
0,05	2,13	1,87	1,50	1,25	1,00
0,10	4,19	3,59	2,94	2,45	2,00
0,15	6,13	5,25	4,37	3,65	3,00
0,20	8,12	6,81	5,75	4,85	4,00
0,25	9,81	8,31	7,06	6,00	5,00
0,30	11,40	9,69	8,31	7,15	5,00
0,35	13,00	11,10	9,53	8,20	6,91
0,40	14,60	12,40	10,70	9,30	7,91
0,45	16,10	13,80	11,90	10,30	8,78
0,50	17,60	15,10	13,00	11,30	6,69

The quantity Alk' may be determined from the formula

$$Alk' = AlK \frac{0{,}01 A^w}{V_g^{en} g'}, \text{ mg-eq/kg} \quad (1\text{-}22)$$

where Alk is the free alkalinity per kg of ash, mg-eq/kg (see Table 1-10);
A^w is the ash content of the working mass of fuel, %;
g' is the specific consumption of spray water per m^3 of gases at standard conditions, kg/m^3.

The coefficient of removal of sulfurous anhydride from the gas may be represented as the ratio of the absorbed SO_2 to the amount of SO_2 present in the flue gases

$$\eta_{SO_2} = \frac{Abs}{Z_{SO_2}} \times 100, \%. \quad (1\text{-}23)$$

Sulfuric anhydride SO_3 is absorbed by water in greater quantities than is SO_2. For practical purposes, it may be assumed that $\eta_{SO_3} \approx 40\%$.

A certain amount of sulfurous anhydride may be trapped in dry ash collectors as a result of partial absorption of SO_2 by ash, in which part of the SO_2 (and also SO_3) is converted into sulfates. Thus, when shales are burned to nonvolatile compounds, almost 40% of the sulfur may be bound.

According to VTI data, the coefficient of absorption of sulfur by ash (or the coefficient of SO_2 removal) may be determined from the following formula:

$$\eta_{SO_2} = 12{,}5 \times 10^{-5} A^d Alk \%, \quad (1\text{-}24)$$

where A^d is the ash content of the fuel in the dry mass, %;
Alk is the alkalinity of the ash, mg-eq/kg (see Table 1-10).

2. Amount of sulfurous anhydride at the entrance and exit from the ash collector:

$$G_{SO_2}^{en} = 0{,}01 B_{av} S^w \frac{M_{SO_2}}{M_S}, \text{ kg/sec;} \quad (1\text{-}25)$$

$$G_{SO_2}^{ex} = G_{SO_2}^{en} - G_{SO_2}, \text{ kg/sec;} \quad (1\text{-}25')$$

$$G_{SO_2}^{col} = \frac{G_{SO_2}^{en} \eta_{SO_2}}{100}, \text{ kg/sec.} \quad (1\text{-}25'')$$

1-5. Coefficients of Purification of Gases in Dust and Ash Collectors

The coefficient of purification (otherwise referred to as the degree of purification or dust collector efficiency) gives the ratio of the weight of the dust collected in the dust collector to the weight of entering dust.

$$\eta = \frac{G_{col}}{G_{en}} \times 100 = \frac{G_{en} - G_{ex}}{G_{en}} \times 100 = \frac{G_{col}}{G_{col} + G_{ex}} \times 100, \ \%. \tag{1-26}$$

The determination of the purification coefficient is the final step in the design of dust collectors. By using it one can evaluate the efficiency of removal of dust of a certain particle size composition from a gas in a dust collector of a given design. The value of η obtained (total purification coefficient) may change with the coarseness of the dust.

The efficiency of a dust collector of a given design is characterized by the fractional and partial purification coefficients attainable through its use. The fractional coefficient gives the ratio of the amount of dust of a given fraction collected in the device to the amount of entering dust of the same fraction. The partial coefficient involves dust of certain particle dimensions (diameters):

$$\eta_f = \frac{G_{f_{col}}}{G_{f_{en}}} = \frac{F_{col} G_{col}}{F_{en} G_{en}} = \frac{F_{col}}{F_{en}} \eta; \tag{1-27}$$

$$\eta_p = \frac{G_{N_{col}}}{G_{N_{en}}} = \frac{N_{col} G_{col}}{N_{en} G_{en}} = \frac{N_{col}}{N_{en}} \eta. \tag{1-28}$$

The fractional (partial) purification coefficients for different particle sizes are determined experimentally or theoretically for dust collectors of different types and sizes, and their values must be known.

The total purification coefficient may be calculated from the fractional (partial) composition of ash or dust entering the dust collector and from the fractional (partial) purification coefficients:

$$\eta = \Sigma \eta_f \frac{r_{en}}{100}, \ \%; \tag{1-29}$$

$$\eta = \Sigma \eta_p \frac{N_{en}}{100} \Delta x, \ \%. \tag{1-30}$$

In calculations with the formula it is necessary that the size intervals for the dust composition and for the fractional purification coefficients be the same. Instead of η_f one can use η_p for the average value of x for the

interval. The sums F_{en} [in formula (1-29)] and $N_{en}\Delta x$ [in formula (1-30)] should each amount to 100%.

Frequently, the fractional or partial purification coefficients characteristic of a device are known for particles with a density differing from that of the ash or dust susceptible of collection. In this case the conversion from particle size d_{kn} with density ρ_{kn}, for which the partial or fractional purification coefficients are known, to the actual size of the particles d_{act} with density ρ_{act}, for which these coefficients will be valid, is accomplished by using the following relation:

$$d_{act} = d_{kn} \sqrt{\frac{\rho_{kn}}{\rho_{act}}}. \tag{1-31}$$

Formula (1-30) may be written more accurately as

$$\eta = \int_0^\infty \eta_p \frac{N_{en}}{100}\, dx, \ \%. \tag{1-32}$$

In designing a composite dust collector consisting of two (or more) units of different types mounted in sequence, it is necessary to determine the fractional composition of the dust leaving the preceding stage and entering the next stage. In this case, each fraction is recalculated by using the formula

$$\Phi_{ex}^{I} = \Phi_{en}^{II} = \Phi_{en}^{I} \frac{100 - \eta_f^I}{100 - \eta^I} \tag{1-33}$$

or

$$N_{ex}^{I} = N_{en}^{II} = N_{en}^{I} \frac{100 - \eta_p^I}{100 - \eta^I}, \tag{1-34}$$

where η_p^I and η_p^I are respectively the fractional and partial coefficients of gas purification in the first stage, %; η^I is the total coefficient of gas purification in the first stage, %.

The total gas purification coefficient in the second stage is calculated by taking into account the fractional composition of the dust entering the second stage.

The total (overall) coefficient of gas purification in a two-stage dust collector is given by the formula

$$\eta^{tot} = \eta^I + \eta^{II}\left(1 - \frac{\eta^I}{100}\right), \ \%. \tag{1-35}$$

PRINCIPLES OF DESIGN OF GAS PURIFICATION SYSTEMS

A. P. Anastasiadi

From "Ochistka dymovykh gazov v promyshlennoy energetike". A. A. Rusanov, I. I. Urbakh, and A. P. Anastasiadi. "Energiya", Moskva, p. 189-206, (1969).

6*-1. General Background

The presence in flue gases of certain concentrations of solid particles depends on the type of fuel and methods of its combustion, the design characteristics of the furnace systems, the efficiency with which the furnace process is carried out, and the type of fuel-consuming unit and its operating conditions. The struggle against atmospheric pollution should be waged along three major lines: first, improvement of the design of fuel-consuming installations and optimization of their operating conditions; second, by installing suitably chosen ash and dust collectors, and third, by installing sufficiently high smokestacks in order to disperse the fly ash and dust over considerable distances and areas and thus to decrease their harmful effects.

The choice of dust and ash collectors to be included in a system of purification of flue gases depends on a number of factors. The main factors are the type and capacity of the boiler or other industrial heat-engineering unit, the type of fuel and method of its combustion, the presence in the flue gases of carryover of the material being treated in the technological unit, the physicochemical properties of the carryover, the most efficient method of dust and ash removal, the possibility of a convenient combination of gas purification equipment, and the required degree of gas purification.

The limited number of designs of steam or furnace boilers commonly used in the power industry has led to the formulation of certain recommendations for selecting ash collection systems for them as a function of the type of fuel burned.

In this section we shall indicate only that boiler houses burning solid fuel should be equipped with devices for the removal of ash from the flue gases when the value N of the conventional characteristic of the boiler exceeds 5000,

$$N = A^W B$$

where A^W is the ash content of the working mass of fuel, %;
B is the maximum hourly estimated fuel consumption, kg/hr.

*Editor's note: The first digit represents chapter numbers.

If N is less than 5000, the installation of ash collectors is required only if the boiler house is located in a residential area. When solid fuel is used only for emergency purposes, ash collectors usually are not installed.

Owing to the relatively small absolute quantity of ash discharged, boiler units usually make it possible to make use of gas purification devices of moderate efficiency, but on the other hand of low hydraulic resistance, capable of operating on the natural draft generated by the smokestack.

In industrial heat-engineering units, in addition to the necessity of ensuring the purification of waste gases for sanitary purposes, the selection of the system of dust-collecting equipment is frequently determined by the conditions of recycling of the trapped product. The use of trapped dust in industry increases the motivation of personnel in trying to achieve a good performance of the gas purification system.

The concentration of noxious substances in the air of the breathing zone may be reduced by increasing the height of the stack discharging the flue gases into the atmosphere. The higher the stack, the lower the concentration of noxious substances near the earth. A high smokestack not only decreases the concentration, but also pushes back the start of the pollution zone. However, by building high stacks for discharging the waste gases into the atmosphere, one can lower the concentration of noxious substances to the maximum permissible values only for a small part of the installations; in the great majority of cases, a combination of efficient dust collectors and a smokestack of suitable height determined by calculation is required.

Before starting the design of a gas purification system, one must make a thorough study of the design and operating characteristics of the dust and ash collectors developed thus far. Those most commonly employed are discussed in the preceding chapters. A whole series of other devices that may be more suitable in specific cases can be found in the book by V. N. Uzhov [18] and elsewhere.

The selection of dust collectors must be made in each individual case on the basis of the technical and economic indices of the dust-collecting system. Each dust-collecting device is built and designed for a given set of operating conditions. Therefore, in comparing a given dust-collecting device, it is necessary to think in terms of devices designed for operation under the same technological conditions.

Thus, for the purification of flue gases from boiler houses, the comparison is made between cyclones, multicyclones, and TsS-VIT scrubbers of approximately the same efficiency that is adequate for the case under consideration. When it is necessary to achieve fine cleaning of large volumes of gases from boilers of medium and large steam capacity, one can compare PGD and PGDS type electrostatic precipitators MP-VTI type ash collectors, and in some cases bag

filters. When it is necessary to purify gases from industrial heat-engineering units, which are characterized by the widest range of gas discharge and required efficiency of dust collection, in addition to the units enumerated above one can compare type Ts electrostatic precipitators, foam devices, high-speed gas washers, etc.

When the designing is started, a whole series of initial data must be collected. Then, it is necessary to draft the possible layouts of the gas purification system and carry out alternative calculations to permit the selection of the optimum version from the standpoint of expected efficiency, hydraulic resistance, capital and operating costs, composition of the equipment, etc. To facilitate the preliminary selection of devices in the drafting of possible layouts of a system of purification of flue gases, Table 6-1 gives some average technical economic indices for some of these layouts.

Table 6-1

Average Technical-Economic Indices of Dust Collectors.

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Dust Collector	Degree of Purification, %	Hydraulic Resistance, n/m²	Consumption Expended on Purification 1000 m³/hr, of		Cost of Purification, 1000 m³/hr	
			Electrical energy, MJ	Water, ℓ	Estimated, rubles	Operating, kopeks
VTI louver-type ash collector	60	470	0,93	—	15	0,64
NIIOGAZ cyclone	80	470	0,93	—	130	0,75
Multicyclone	80	500	1,0	—	90	0,51
TsS-VTI centrifugal scrubber	90	650—800	1,1	140	90	0,98
MP-VTI wet-rod ash collector	92	800	1,3	130	60	0,80
Foam scrubber	95	400	1,1	300—900	130	1,1
High-speed gas washer	90	$5 \cdot 10^3$—$10 \cdot 10^3$	11—21	300—900	20	3,5
Bag filter	99	1 000	1,5	—	175	1,72
DVPN vertical-type electrostatic precipitator	90	150	0,57	—	265	0,99
DVPN-BTs composite electrostatic precipitator with multicyclone	98	600	1,3	—	300	1,34
PGD-type three-pole horizontal elect. precip.	96—98	150	0,93	—	350	1,09
Ts two-pole horizontal electrostatic precipitator.	97—98	150	2,5	—	580	2,43

The figures taken from the table should subsequently be corrected by suitable calculations for specific conditions. The degree of gas purification in Table 6-1 is given for dusts with the most frequent average particle size. Therefore, if information on the actual particle size composition of ash or dust to be collected is available, one can use the corresponding column of Table 6-1 and refer to Table 6-2, which gives average values of partial purification coefficients for different devices.

Table 6-2

Partial Purification Coefficients for Various Devices
(Average Values)

Dust Collectors	Particle sizes, μm			
	50	10	5	1
High-efficiency cyclones	96	85	67	10
Multicyclones	100	96	89	20
Scrubbers	99	96	94	35
Foaming device	100	94	88	60
High-speed gas washer with a large pressure drop	100	>99	>99	97
Dry electrostatic precipitator	99	98	92	82
Cloth filters	100	>99	>99	99

The color intensity of the discharge and its biological noxiousness are chiefly determined by the area of the particles contained therein. Hence the importance of trapping the largest possible amount of fine particles becomes evident, but this also happends to be the range where the efficiency of the dust collectors is lowest. Table 6-2 shows that the cyclones most frequently used for dust and ash trapping have an efficiency of the order of 10% for particles of 1 μ (this being characteristic of dust from sublimation), and only high-speed gas washers, cloth filters and electrostatic precipitators have a high efficiency for particles of this diameter.

In combining dust-collecting equipment, the following guidelines should be used.

The dust collectors are usually installed on the suction side of flue gas pumps. The installation of dust collectors on the delivery side of the pumps is possible, but is not recommended, since in this case the pumps are subjected to abrasive wear.

For convenience of servicing and repair of dust-collecting equipment, individual dust collectors should be mounted, as a rule, on every processing unit.

When a boiler house operates on solid fuel only, the individual ash collectors should not have any gas conduits or horizontal flues surrounding them. When a boiler house operates on gas fuel, with the utilization of fuel as a reserve, the ash collectors are placed on horizontal flues surrounding them or on gas conduits. The main flues or gas conduits should be equipped with reliable devices for disconnecting them during operation on solid fuel.

Dust- and ash-collecting devices may be installed both inside buildings and outdoors. One must then consider the climatic conditions of the area, the periodicity of operation, type of apparatus used, and the volume of the gas being purified. In practice, however, the majority of dust and ash-collecting devices may operate outside buildings. For example, most electrostatic precipitators that are the most complex from the standpoint of design and operating characteristics are installed outside the boiler house. However, to protect the insulating housings from deposits and to facilitate their servicing, the top of the electrostatic precipitator is covered by a tent. The space under the hopper is also covered with light materials. As a rule, cloth filters and foam devices are mounted inside buildings.

Characteristics of Two-Stage Purification of Gases Using Electrostatic Precipitators

Experiences with the operation of electrostatic precipitators in different branches of industry shows that in the presence of a high initial ash or dust concentration in the flue gases (over 40-50 g/m^3), the efficiency of the purification decreases. This may be due to a rapid build-up of precipitated material on the discharge and collecting electrodes, making it necessary to increase the frequency with which they are shaken off, and thus resulting in an increase of secondary carry-over.

In order to decrease the concentration of carryover in the gas fed to the electrostatic precipitators and hence to ensure a more reliable and stable operation of the precipitators, the use of preliminary (rough) purification of flue gases in mechanical ash collectors with a low hydraulic resistance, for example, cyclones or direct-flow cyclones, is recommended. Doubts are sometimes expressed concerning the usefulness of installing a preliminary gas purification stage, since in this case mainly fine carryover particles will reach the electrostatic precipitators. And, since the adhesive properties of fine carryover particles are much less obvious than those of coarse particles, serious difficulties will arise in attempts to remove them from the electrodes of the devices, and the degree of purification of the flue gases will be decreased. In any case, in the German Federal Republic, the installation of a multicyclone as the first stage of purification before the electrostatic precipitators is recommended only in cases where the content of combustibles in the carryover exceeds 20%. However, even then the following conditions must be met: the efficiency of ash collection of the first purification stage should not be too high, so that the conductance of the carryover is sufficient to ensure a stable operation of the successive electrostatic precipitators and to prevent the electrodes of the latter from being grown over with the fine particles of the carryover.

Results of the operation of electrostatic precipitators at a number of Soviet power plants where preliminary purification of gases in mechanical

devices is employed have demonstrated that such doubts and apprehensions are not always well-founded.

First, when multi-ash fuels are burned, the mere installation of an electrostatic precipitator, even when a relatively high efficiency is attained, does not always ensure the sanitary standards of purification of the flue gases, whereas the installation of a preliminary purification stage, even though the overall degree of purification is increased by only a few percent, makes it possible to reach the permissible standards of residual concentration of the carryover in the purified gas.

Second, the presence of a first purification stage makes it possible to cut down considerably on the discharge of fly ash into the atmosphere whenever the electrostatic precipitators must be disconnected for whatever reason, since the preliminary stage usually ensures a 60-80% efficiency of ash collection.

As far as any serious risks to the stable and efficient operation of electrostatic precipitators should fine carryover particles penetrate into them, the following example may be mentioned: in the combustion of high-energy coals in furnaces with a slag removal coefficient of about 80-90%, the gases leaving the boiler unit contain a comparatively large amount of fine carryover particles, but the degree of purification of the flue gases by the electrostatic filters remains quite high [47, 50].

It should be noted that statements are frequently made to the effect that the installation of a two-stage purification system is undesirable because it raises the cost of construction and assembly and the operating cost. However, in several countries and particularly in the U.S.A., a two-stage purification system of 99% efficiency is a relatively common method of ash collection [55].

In solving the problem of selection of a given gas purification system, in addition to the economic considerations, one should take into account the sanitary conditions. In general, according to the recommendations of the State Institute for the Design and Planning of Structures for Gas Purification, the preliminary purification of flue gases in mechanical devices should be carried out when the initial dust content of the gases is above 40 g/m^3.

6-2. Relationship Between the Height of Smokestacks and the Required Efficiency of Gas Purification

The height of smokestacks of electric power plants and other fuel-consuming enterprises should ensure a dispersal of ash, dust, sulfur dioxide or other noxious impurities such that their concentrations at ground level drop below the maximum permissible values (Fig. 6-1).

For the same amount of polluting solid impurities in the flue gases at the exit from the boiler or other industrial heat-engineering unit, the smokestack chosen may be lower the higher the efficiency of the dust-collecting system, and vice versa.

Therefore, in planning industrial power stations, boilers, etc., one of two problems must be solved:

1) the minimum stack height is found from known impurity concentrations in the gases after the gas purification system, and from the maximum permissible concentrations at ground level;

2) the concentrations of noxious impurities which can be permitted at the exits from the gas purification system are found from the accepted stack height and from the maximum permissible concentrations at ground level.

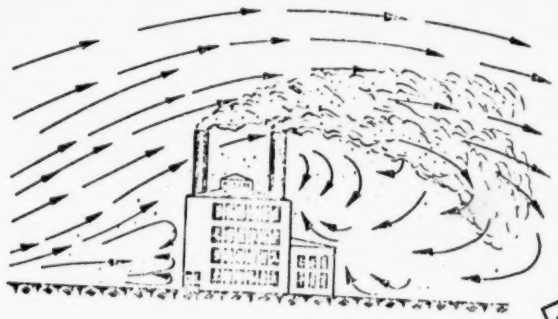
In calculating the dispersal of noxious impurities by smokestacks, use should be made of the "SN-369-67 Recommendations for the Atmospheric Dispersal of Noxious Impurities (Dust or Sulfur Dioxide) Present in the Discharges of Industrial Enterprises", worked out by the A. I. Voyeykov Institute and pertaining to the following enterprises and facilities:

1) boiler houses;
2) sintering ferrous and nonferrous metallurgical plants;
3) pelletizing ferrous metallurgical plants;
4) converter, open-hearth, and electrosmelting plants;
5) blast-furnace production;
6) production of sulfuric acid by the contact process;
7) production of elemental sulfur;
8) petroleum refineries (combustion of fuel oil).

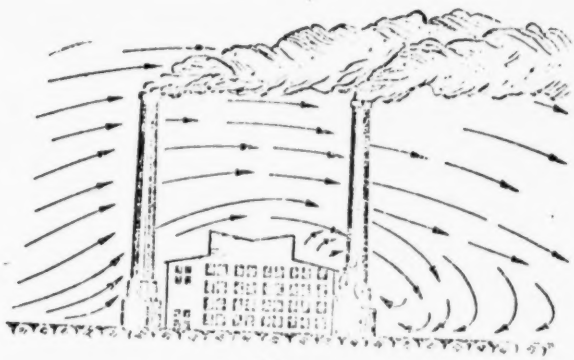
In accord with the Main Sanitary Epidemiological Administration of the Public Health Ministry of the USSR, these recommendations may be used in calculating the dispersal of other noxious substances in the atmosphere and may also be applied to other facilities.

When the atmosphere is polluted by sources whose parameters (see below) are not covered by the calculations indicated by SN-369-67, use may be made of P. I. Andreyev's formula [102].

The methods for calculating the dispersal of noxious substances in the atmosphere are based on the determination of the concentration of these substances in the ground layer of air.



a)



b)

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Fig. 6-1. Diagram of dispersal of fly ash from flue gases.
a - low smokestacks; b - high smokestacks.

The degree of danger of polluting the ground layer of air with discharges of noxious substances from industrial enterprises and boiler houses is determined from the highest ground concentration of noxious substances c_m, which may form at a certain distance from the point of discharge under unfavorable weather conditions (when the wind velocity reaches the unsafe value and an intense vertical turbulent exchange takes place).

The values of c_m (in mg/m^3) for each of the substances should not exceed the highest single maximum permissible concentrations of these substances in the atmosphere of populated areas (MPC): $c_m \leq \underline{MPC}$.

The MPC values should be taken from the "Sanitary Norms for the Design of Industrial Enterprises (SN-245-63)".

The single MPC's now provide the basic appraisal of the danger of substances having no cumulative action.

For sulfur dioxide and for nontoxic dust, the single MPC's are taken as 0.5 mg/m^3.

Calculation of Atmospheric Concentration of Dust and SO_2 Discharges from Smokestacks According to SN-369-67 Recommendations

Under favorable weather conditions and for a level or slightly dissected topography, the maximum single concentration from N stacks of the same height at a distance of 20 stack heights is given by the formula

$$c_m = \frac{AFmM_s}{H^2}\sqrt[3]{\frac{N}{Q\Delta t}}, \quad mg/m^3 \qquad (6\text{-}1)$$

where A is a coefficient dependent on the temperature stratification of the atmosphere and defining the conditions of vertical and horizontal dispersal of the impurity in air, sec$^{2/3}$ deg$^{1/3}$;

F is a dimensionless coefficient of the physical state of the noxious substance;

m is a dimensionless coefficient taking into account the influence of the exit velocity of the gas at the orifice of the discharge source (stack);

M_t is the maximum total discharge of the noxious impurity from all the stacks, g/sec;

H is the geometric stack height, m;

N is the number of stacks of the same height;

Q is the total volume of the flue gases discharged from all the stacks, m^3/sec;

Δt is the difference between the temperature of the gases leaving the stack t_g and the temperature of the surrounding air t_a, °C.

A method of selection and calculation of these quantities is given below.

Coefficient A is taken for unfavorable weather conditions, when the wind velocity reaches the unsafe value V_m and an intense vertical turbulent exchange takes place. At the same time, the ground concentration of the noxious substances in air reaches its maximum value.

The following values of A should be taken in the calculations:

For the Caucasus, Central Asia, Siberia, Lower Volga and Far East	200
For the North and Northwest of the European Territory of the USSR, Ural, Ukraine and Middle Volga	160
For the Central part of the European Territory of the USSR and regions with similar climatic conditions	120

In other areas of the territory of the USSR, the values of coefficient A should be taken on the basis of the similarity between the climatic conditions of turbulent exchange in these areas and those mentioned above.

If according to the data of the hydrometeorological service unfavorable local weather characteristics are present, the values of ground concentrations of noxious substances should be increased by 25% in the calculations in accordance with the existing scientific and industrial experience.

The value of coefficient F as a function of the efficiency of the dust-collecting system η and for SO_2 is given below.

Impurities	SO_2	Ash for $\eta > 90\%$	Ash for $\eta \leq 90\%$
F	1,0	2,0	2,5

Coefficient m should be determined from parameter f by means of the graph given in Fig. 6-2.

The applicability of formula (6-1) is restricted by a condition according to which the parameter

$$f = \frac{10^3 w_0^2 D}{H^2 \Delta t}, \quad \text{m/sec}^2 \text{ deg}, \qquad (6\text{-}2)$$

where w_0 is the exit velocity of the gas from the mouth of the stack, m/sec, and D is the diameter of the orifice of the stack, m, should satisfy the inequality $f<6$.

In determining the difference Δt between the temperature of the discharged gas mixture t_g and that of the surrounding air t_a it is necessary to assume the temperature of the surrounding air to be the average temperature of the hottest month at 1 P.M.

For boiler houses operating in accordance with the thermal graph, the average temperature of the heating period may be taken in the calculations.

The concentrations of noxious substances calculated on the basis of the present official recommendations pertain to steady conditions of propagation of the impurity retained in the atmosphere above a level or slightly dissected topography (with slopes of not more than 2-3°). In planning enterprises to be located on rugged terrain, it is necessary to resort to special recommendations for the calculation of the dispersal of noxious substances in the atmosphere compiled by the Main Geophysical Observatory im. A. I. Voyeykov of the Main Administration of the Hydrometeorological Service, Council of Ministers

of the USSR, and the Main Sanitary Epidemiological Administration of the Ministry of Public Health of the USSR.

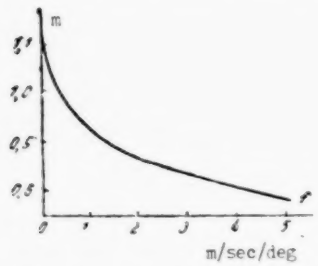

Fig. 6-2. Graph for determining coefficient f.

The maximum concentration of noxious substances at ground level under unsafe meteorological conditions is reached at a distance X_m from the source, this distance being determined in terms of the stack height H from the formula

$$X_m = 20H, \text{ m}. \qquad (6\text{-}3)$$

Concentrations of noxious substances differing from the maximum value by not more than 30% are observed at distances of (10-40) H.

The unsafe wind velocity V_m at a height of 10 m above ground level, at which the highest ground concentration of noxious substances in air is reached, is approximately given by the formula

$$V_m = 0{,}65\sqrt[3]{\frac{Q\Delta t}{NH}}, \text{ m/sec}. \qquad (6\text{-}4)$$

Usually, the wind velocity at the height of 10 m is 0.5-10 m/sec. For V_m = 2 m/sec, the flue gases rise vertically upward, and for V_m = 9-10 m/sec, the flue gases are sheared off the stack orifice and move parallel to the ground at the level of this orifice. More accurate calculations show that the estimated unsafe velocity V_m is slightly higher than that calculated from the formula and is dependent on parameter f. When f<1, the unsafe velocity is approximately 10% higher, and when 1<f<6, approximately 20% higher.

The maximum concentration c_{mV} of noxious substances in the ground layer of atmospheric air under unfavorable weather conditions at wind velocity V different from V_m is given approximately by the formula

$$c_{mV} = rc_m. \qquad (6\text{-}5)$$

The dimensionless coefficient r as a function of the ratio V/V_m is determined from the graph given in Fig. 6-3.

The distance from the source X_{mV} at which the ground concentration of noxious substances reaches its maximum value c_m at wind velocity V is given by the formula

$$X_{mV} = PX_m. \qquad (6\text{-}6)$$

The dimensionless coefficient P as a function of the ratio V/V_m is determined from the graph of Fig. 6-3, c_m being found from formula (6-1) and X_m from formula (6-3).

The above-described approximate method for calculating the change of the concentration of noxious substances in atmospheric air can be used only when the smokestack orifices are located much higher than the rooftops of the surrounding buildings. When the stack orifice is located relatively low above the roof of the boiler house (Fig. 6-1a), the smokestack is in the zone of eddy formation, located on the leeward side of the buildings, and the general pattern of propagation of the jet is disturbed; the concentration of noxious impurities in this case may be much higher than in the case of propagation of the smoke jet assumed in the derivation of formula (6-1) and illustrated in Fig. 6-1b.

The general laws of propagation of a smoke jet are also inapplicable to a mountainous topography, especially when the boiler house is located at the foot of a mountain or hill. In this case, the direction of motion of the smoke jet (its axis) may be parallel to the slope of the mountain (when the wind blows from the mountain toward the stack), and the stack gases may reach the ground much faster than in the case of a level topography.

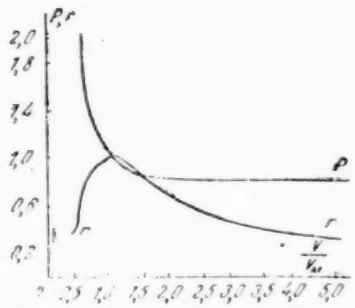

Fig. 6-5. Graph for determining r and F.

When expanding a boiler house or planning a new enterprise with the discharge of noxious impurities taking place in an area where atmospheric air has already been polluted with the same impurities from other industrial plants, it is necessary to consider the background concentration c_b. In this case, the sum $c_b + c_m$ must not exceed the MPC (maximum permissible concentration).

The value of the background concentration is established by agencies of the Sanitation Inspection.

If several enterprises are located on a single straight line (with a deviation of not more than 1-1.5 H), then at the point of the assumed concentration maximum the values of c_b are obtained as the total concentration from these enterprises.

When the enterprises are not located on the same straight line, the determination of c_b is made at the point of the assumed maximum on each curve connecting the given enterprise with the facility under construction. The value which is then taken for c_b is the highest value found for each of the straight lines separately.

The calculation of the maximum concentration for power plants and enterprises with stacks of different heights and different discharge parameters is performed as follows. For each of the stacks, c_m and X_m are first determined

by means of the graph given in Fig. 6-4, and curves of the change of concentration c with distance X are plotted. The curves for each of the stacks are then superimposed on a single graph with a common origin of coordinates. Values of c from all the stacks are then summed up for the values of X, and the total value is found as a function of distance X. The highest value represents c_m for the entire system of stacks, and the corresponding value of X_m represents the distance at which the maximum of the total concentration is reached.

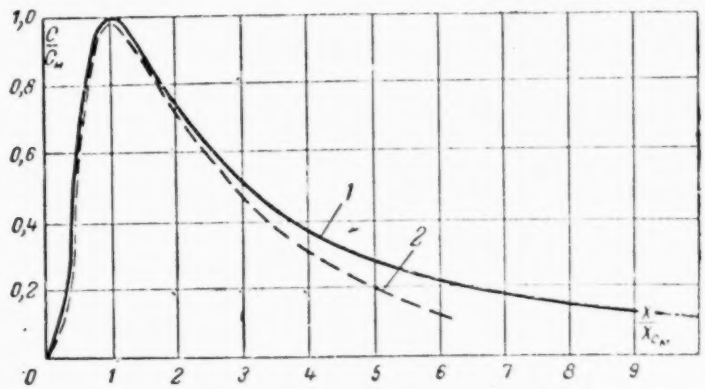

Fig. 6-4. Distribution of the concentration of discharges from a smokestack at ground level.
1 - sulfur dioxide; 2 - ash

In cases where individual gas purification units are planned without a determination of the total single concentrations of the substances from all the sources producing the background pollution, the degree of purification of the discharges containing dust is established as a function of the maximum permissible dust concentration in the air of the work zone of the plant buildings.

Maximum permissible concentration of dust in the air of the work zone in plant buildings, mg/m³	Permissible content of dust in the air discharged into the atmosphere, mg/m³
2 and less	30
More than 2 to 4	60
" " 4 " 6	80
" " 6 " 10	100

When the concentrations of noxious substances in the atmospheric air of populated areas remains within limits not exceeding the maximum single permissible values, the residual amount of noxious substances in the gases discharged into the atmosphere is not standardized.

It has been decided that discharges containing dust with an average size of less than 80 μ in an amount not exceeding the above-indicated permissible dust content in the discharges released into the atmosphere do not have to be purified.

Example. Determination of the required efficiency of an ash collector for an existing smokestack.

Initial data.

The boiler house discharges into the atmosphere stack gases at a rate of	100 m^3/sec
Gas temperature at exit from stack orifice	130°C.
Initial ash content of flue gas	14.0 g/m^3
Geometric height of existing smokestack	80 m
Diameter of smokestack orifice	2.5 m
Allowing for the existing atmospheric background dust content, the permissible ash concentration in the breathing zone should not exceed	0.25 kg/m^3
Location of boiler house - Ukraine, city of Kherson. Average air temperature at 1 P.M. during the warmest month (according to climatological data)	+29°C.

Calculation

Since the temperature of the gas (130°C.) is considerably higher than that of the surrounding air, we check the applicability of the calculation by using parameter f of Recommendations SN-369-67

$$f = \frac{10^3 w_0^2 D}{H^2 \cdot \Delta t}, \text{ m/sec}^2 \text{ deg.}$$

The exit velocity of the gas from the orifice of the smokestack is

$$w_0 = \frac{100 \cdot 4}{3{,}14 \cdot 2{,}5^2} = 20{,}3 \text{ m/sec.}$$

The temperature difference between the gas and the surrounding air is

$$\Delta t = 130 - 29 = 101^\circ \text{C.}$$

Substituting the values into the formula for the determination of the parameter

$$f = \frac{10^3 \cdot 20{,}3^2 \cdot 2{,}5}{80^2 \cdot 101} = 1{,}6 \text{ m/sec}^2 \text{ deg}$$

The value of parameter f satisfies the inequality $f < 6$, and therefore the calculation of the dispersal is done by using the method of Recommendations SN-369-67.

The permissible discharge M_t is determined by the formula

$$M_t = \frac{c_{sa} H^2 \sqrt[3]{Q \Delta t}}{A F m}, \text{ g/sec}$$

where A = 160 $sec^{2/3} deg^{1/3}$ for the Ukraine region;
F = 2 for an ash collector efficiency of over 90%;
m = 0.9 according to the graph given in Fig. 6-2 for f = 1.6 m/sec^2 deg.
Substituting the above-indicated value into the formula,

$$M_t = \frac{0{,}25 \cdot 80^2 \sqrt[3]{100 \cdot 101}}{160 \cdot 2 \cdot 0{,}9} = 119 \text{ g/sec}$$

The maximum permissible residual dust content of the flue gases at the exit from the ash collector is

$$c_{ash}^{ex} = \frac{119}{100} = 1{,}19 \text{ g/m}^2$$

The minimum required efficiency of the ash collector is

$$\eta = \frac{(14 - 1{,}19)\,100}{14} = 91{,}5\%.$$

DETERMINATION OF THE BASIC PROPERTIES OF DUSTS AND GASES

A. A. Rusanov

From "Ochistka dymovykh gazov v promyshlennoy energetike". A. A. Rusanov, I. I. Urbakh, and A. P. Anastasiadi. "Energiya", Moskva, p. 405-440, (1969).

11*-1. Determination of the Dispersity of Ash or Dust

In determining the particle size of ash and dust, the following factors must be distinguished:

a) primary particle size, i. e., the size that characterized the particles at the time of their formation;

b) particle size after a certain coagulation of the particles during the motion of dust-laden gases along the gas conduit;

c) size of particles in the form of flocs and small clumps after their separation from the gas phase.

The efficiency of dust-collecting devices depends on the particle size characteristic of the ash or dust after a certain coagulation of the particles in the gas conduits. The degree of particle coagulation in the gas conduits depends considerably on the initial particle size. The coarser the particles, the less they tend to coagulate; particles over 100 μ in diameter, for example, practically do not coagulate. Therefore, if the content of fine fractions is small, in carrying out calculations of the efficiency of planned dust-collecting devices, one can use data on the particle distribution over the sizes in the gas conduits as well as over the original sizes. When the content of fine particles is considerable, the estimated efficiency of the dust-collecting devices may turn out to be somewhat low if the calculations are made by using data on the distribution of the particles over the original sizes.

There are a number of methods for determining the particle size. Those most commonly used are sieve analysis, air separation, liquid sedimentation, and microscopic analysis. The last few years have seen the development of a relatively approximate determination of dispersity by the method of three cyclones, and a more accurate determination, but with a narrower scope of application to the maximum permissible temperature and dust content of gases, by means of multistage jet settlers. Work aimed at increasing the accuracy of the three-cyclone method and expanding the range of applicability of the multistage jet settlers is continuing.

In the methods of sieve analysis, air separation and liquid sedimentation, the material subjected to analysis consists of dusts separated from the gas phase, i. e., in the form of a deposit. The dust taken in this form is

*Editor's note: The first digit represents chapter numbers.

dispersed by some means so as to obtain particles of the original size, and the size distribution for these particles is then obtained.

The three-cyclone method and multistage jet settlers make it possible to obtain the particle size distribution without their preliminary separation from the gas phase, i. e., the distribution over the sizes that they acquire after a certain coagulation in the dust-laden stream.

The method of microscopic analysis as a function of the method of sampling makes it possible to obtain the particle distribution both over the original sizes and over the sizes of the particles after a certain coagulation in the gas conduits.

Each of the enumerated methods has a certain scope of application that does not always coincide with those of other methods. Therefore, each, despite certain disadvantages, retains its importance.

Sieve Analysis

Sieve analysis is based on sifting the ash or dust sample through sieves with different meshes. The particle size composition of the dust is estimated from the weight of the residue on the different sieves. The metal screens for the sieves are manufactured in the USSR in accordance with GOST 3584-53, the finest screen having a mesh size of 44 μ .

The sieves are in the form of cylindrical shells whose bottom is closed off by the screens, and they are stacked in a column so that the mesh size decreases from the top down. A solid bottom on which the finest fraction is collected is placed under the finest sieve.

The sifting is done either mechanically or by hand.

Mechanical shifting employs a special "Rotap" instrument which shakes the set of sieves fastened inside it. Other machines are also manufactured.

A predried dust sample weighing 25-100 g is placed in the top, coarsest sieve. After the machine has operated for 20 minutes, the residue on each sieve is weighed. The fractions obtained are called incomplete, since the upper sieves retain a part of the dust which would collect completely on each of the lower ones. By plotting the values of incomplete residues in a suitable coordinate system or collecting them in a table (see Fig. 1-1b), one can obtain the fractional distribution of the dust.

The complete residue on each sieve can be obtained as the sum of incomplete residues on the same and upper sieves.

By plotting the values of complete residues in suitable coordinate

systems (see Fig. 1-1 c and d), one can obtain curves characterizing the particle composition of the dust, which in sieve analysis are termed curves of complete residues on sieves.

Manual sifting is done on each sieve successively, beginning with the finest, or on a small assortment of sieves. The sieves are closed off with a bottom plate and with a lid. During the sifting, two or three brief back-and-forth movements should be made in the horizontal plane, then the sieve should be shaken by lightly tapping the bottom plate against the table and tilting the sieve at an angle. The sifting is complete when, after checking by shaking the sieve over a sheet of paper, not more than 0.1% of the weight of the dust for a given sieve falls on the paper.

Since the finest sieve has a mesh size of 44 μ, sieve analysis is applicable only to dusts whose bulk is made up of particles coarser than 45 μ. When sieve analysis is performed, it should be assumed that dust particles less than 10-20 μ in size may coalesce into coarser solid agglomerates during the sifting, causing substantial errors because of the resulting high results for the coarse fractions. For this reason, in cases where the dust contains less than 1% of particles coarser than 60 μ, sieve analysis should not be employed.

Air Separation

This method of determination of the size distribution of dust is based on the fact that particles of different sizes have different hovering velocities and hence are carried out of a vertical tube by a laminar air stream at different velocities of the latter. The hovering velocity is the free-fall velocity of particles in stationary air. A nomogram for determining the particle diameter from their hovering velocity is illustrated in Fig. 3-10*.

The instrument for determining the sizes of particles from their hovering velocity usually consists of three or four vertically mounted tubes of different diameters about 1 m high.

On the top and bottom, the tubes have conical parts ending in nozzles. The lower nozzle can be connected by means of a rubber tubing to an attachment for stirring up the dust studied, and the upper nozzle is connected to a paper filter holder analogous to those used in the determination of the dust content of gases.

Clean air is blown through the tubes with connected attachments for stirring up the dust and with filters. By varying the velocity of the air supplied for stirring up the dust and the tube diameter, one can achieve a state in which only particles with sizes for which the hovering rates are less than or equal to the velocity of the air in the tubes are carried out of the dust stirred up in the attachment and into the paper filter.

*Editor's note: This figure is not available in the section translated.

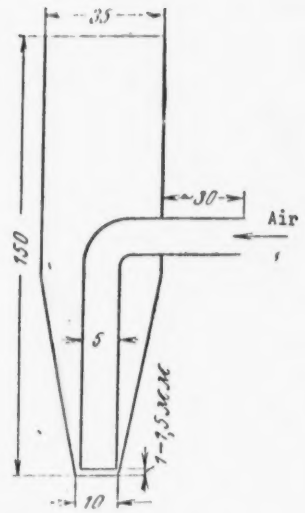

Fig. 11-1. Attachment for stirring up dust.

The most frequently used instrument consists of three tubes with inner diameters of 140, 70 and 35 mm and the stirring attachment illustrated in Fig. 11-1.

The maximum quantities of air that can be supplied to each tube are determined from the condition of laminar flow

$$Re = 2\,300 = \frac{\bar{w}_{max} D}{\nu}, \qquad (11\text{-}1)$$

where $\bar{w}_{max}$ is the maximum mean velocity of the gas in the tube at which the laminarity of the flow is retained, m/sec;

D is the tube diameter, m;

ν is the kinematic viscosity of air, m^2/sec.

Along the tube axis, the velocity will be twice as large as the mean value

$$\bar{w}_{max} = 2\bar{w}$$

In determining the size composition of the dust by the air separation method, the following procedure is used:

1. The fractions into which it is desirable to divide the dust under study are specified.

2. A nomogram is used to determine the hovering velocity for the maximum size particles entering into the composition of each fraction.

3. Air flow rates are calculated which must be supplied to any of the tubes in order to obtain along the tube axis the velocities corresponding to the hovering velocities of the maximum-size particles entering into each of the specified fractions. It is necessary that these discharge rates be included in the above-indicated range, as determined by the conditions of laminarity of the flow and stirring up of the dust. This can be done by using tubes of different diameters.

4. A weighed amount of thoroughly dried dust from 2 to 10 g is loaded into the attachment.

5. The paper filter is weighed.

6. The attachment and filter are mounted on the tube, for which the velocity permitting the entrainment of the finest of the specified fractions is calculated.

7. Air for the entrainment of the finest fraction is passed through the tube with the attachment and filter. During the entrainment, the tube and attachment should be periodically tapped with a wooden hammer having a rubber tip. Instead of tapping the attachment, it is preferable to connect it to a vibrator. The entrainment of the fraction is considered complete when the weight increase of the filter during the course of an hour ceases to increase by more than 1% of the original weight of the dust loaded into the attachment. The entrainment of a single fraction lasts up to several hours.

8. The weight fraction of the entrained fraction is determined in percent. The entrainment of the next fraction is then carried out. The weight fraction of all the dust fractions is thus obtained. The weight of the dust remaining in the attachment and on the tube walls corresponds to the weight fraction of particles with sizes greater than the maximum particle size entering into the last of the entrained fractions.

In order to reduce the settling of the dust particles on the walls, the metal tubes should be grounded.

Each type of dust corresponds to an experimentally determined optimum moisture content of air at which there is a minimum adhesion of fine particles to the tube walls. The moisture content of the air supplied for the entrainment of the dust may be controlled by passing part of it through water or a concentrated solution of sulfuric acid.

The flow rate of air is controlled by means of a rheometer or rotameter.

The pretreatment of the air entering the separator, the velocity of the flow in the latter (mean or maximum), the method of tapping, etc., have not been standardized. Each institute or organization which carries out the analysis employs its own procedure. Studies made by Yu. I. Chicherin at the State Scientific Research Institute of Gas Purification for Industry and Sanitation (NIIOGAZ) have shown that this causes appreciable differences in the results of the particle size analysis of one and the same dust carried out in different institutes.

Liquid Sedimentation

The settling rate of solid particles in a liquid under the influence of the force of gravity depends on their geometric dimensions, density of the particles, density of the liquid in which the particles settle, and its viscosity. The method of determination of the fractional composition of dusts,

based on the observation of the settling rate of particles in a liquid, is called the sedimentation method. It can be used only when the following condition is fulfilled:

$$\mathrm{Re} = \frac{dw\rho_\ell}{\mu} = \frac{dh\rho_\ell}{\tau\mu} < 0{,}2, \tag{11-2}$$

where Re is the Reynolds number;

d is the particle diameter, m;

w is the fall velocity of the particle, m/sec;

h is the height from which the particle falls, m;

ρ_ℓ is the density of the liquid, kg/m^3;

τ is the settling time, sec;

μ is the dynamic viscosity of the liquid, g sec/m^2.

To determine the dispersity of dust containing a substantial amount of other fine particles, in order to satisfy the condition expressed by equation (11-2), it is necessary to use liquids of low viscosity (for example, acetone). The liquids should be chemically neutral toward the dust studied. The concentration of particles in the liquid should not exceed 2%. The size of an individual particle may be determined from its settling rate by means of the formula [69]

$$d = \sqrt{\frac{18h\mu}{g(\rho_d - \rho_\ell)\tau}}, \tag{11-3}$$

where ρ_d is the density of the dust particle;

$g = 9.81$ m/sec^2 is the acceleration due to gravity.

The remaining symbols are the same as in equation (11-2).

The values of μ, ρ_d and ρ_l are usually known, and therefore, by determining the velocity $w = h/\tau$, one can find the size of the solid particle. However, a direct determination of the settling rate of an individual particle is difficult. In a polydisperse dust, particles of all sizes settle simultaneously, but at different rates, and thus indirect methods are required to determine the unknown quantities.

In sedimentation analysis, the particle size distribution may be found by one of the following methods:

1) weighing of the settling particles at certain time intervals (method of N. A. Figurovskiy);

2) use of a sedimentation pipet;

3) study of the change of the density of the liquid during sedimentation.

The methods most commonly adopted involve weighing of the settling particles and use of the sedimentation pipet.

In studying the particle size distribution by the first method, it is convenient to use an instrument consisting of a glass cylinder containing a small glass dish which is attached to a sensitive balance by means of a fine rod. A torsion balance or a fine glass pointer may be used. The degree of deflection of the pointer under the load should be directly proportional to the weight of the load. The pointer should hold the weight of the dish submerged in the liquid plus ~1 g. The deflections of the pointer under the weight of the particles settling on the dish should be recorded by means of a horizontal microscope, for example type MG. It is desirable to have a pointer with a sensitivity of 5 mg per division of the microsccpe ocular reticle. By weighing the settled particles at certain time intervals one can find the dispersity of the dust studied.

The second method of studying the particle size distribution involves the use of the Andreasen sedimentation pipet, illustrated in Fig. 11-2. It consists of a calibrated cylinder 6 cm in diameter filled with the sedimentation liquid (volume, 550 cm^3). On the stopper closing the cylinder is mounted a 10 cm^3 pipet, which makes it possible to collect the sample at the same depth at certain given time intervals.

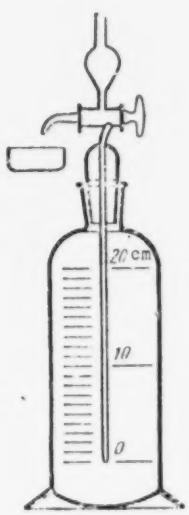

Fig. 11-2. The Andreasen sedimentation pipet.

The weight of the dust introduced into the sedimentation liquid is usually 5-10g. By taking the samples from the same depth at equal time intervals and measuring the concentration of the suspension, one can find the dispersity of the dust studied.

The preparation of the sample for sedimentation analysis consists in the following. A weighed amount of dust is crushed with a rubber stopper in a porcelain cup with a few millimeters of liquid until the lumps disappear. The suspension obtained is placed in a cylinder in which the settling will take place, and liquid is added to the desired level. If flocs are formed in the suspension, a stabilizer should be added or a different liquid used. For water, soda can be used as the stabilizing additive. The suspension is thoroughly stirred up. If the sedimentation is carried out by using the first method, a dish attached to a balance is quickly placed in the stirred-up suspension, the balance lock is released, a stopwatch is turned on, and the recording of readings at exact intervals is started.

The balance with the suspended dish should be set at zero before the suspension is introduced into the cylinder.

If the sedimentation study is done by the second method, a pipet is used to withdraw the same volumes of liquid from the cylinder with the stirred-up suspension at a given depth and at precise time intervals in order to determine the concentration of the suspension.*

The results obtained should be processed in the following manner. A settling curve is plotted on graph paper. The readings of the balance or concentrations of solid particles in the suspension are laid off along the ordinate axis, and time in minutes is laid off along the abscissa axis. After the settling curves have been plotted, the settling time of the particles of a given size, for example, 5, 10, 20, 30, 40, and 50 μ, is calculated. Tangents are then drawn through the corresponding points of the curve, and the points of intersection of these tangents with the ordinate axis are marked. The intercepts defined by the tangents are converted to percentages of the maximum value laid off along the ordinate axis, giving the percent content of the fractions.

An automatic liquid sedimentograph using an electromagnetic analytical balance automatically recording the weight of the sediment in the form of a continuous settling curve was developed in 1957 at the NIIOGAZ under the direction of Yu. I. Chicherin. This device permits one to perform the analysis with a very slight concentration of the dispersed phase, and as a result, the coagulation processes are minimized to such an extent that in many cases it is possible to do without stabilizing additives, which are quite difficult to select correctly. In addition, the analyses are simpler to perform, and the accuracy of the results obtained increases as a result of elimination of the subjectiveness of the readings and some other factors. The automatic sedimentograph affords a high reproducibility of the results obtained and differs conveniently in the simplicity of its actuating mechanisms from instruments proposed earlier. It consists (Fig. 11-3) of a type ADV-200 analytical balance a photorecording attachment, a recording instrument, a power supply and a cabinet for carrying out the analyses.

A round mirror 1, 6-8 mm in diameter, one half of which is blackened, is mounted on the beam of the ADV-200 balance. A solenoid 5 with a permanent magnet 6 suspended inside it is attached to the balance column by a bracket. From the bottom of the balance pan on a fine wire is suspended a dish 12, immersed in cylinder 11 containing the suspension. The finer the wire, the smaller are the errors resulting from the evaporation of the liquid.

On the upper glass plate of the analytical balance is placed a photoelectric recording attachment consisting of an illuminator 2, photocell 3 and electron tube 4. A millivoltmeter or electronic potentiometer 7 can be installed for automatic recording of the weight change. The apparatus is

*A sedimentation instrument with a rising pipet has been developed at the Leningrad Scientific Research Institute for the Organization and Protection of Labor (LIOT) [111].

powered by both line current (through a voltage stabilizer) and BAS-80 dry batteries (8 and 10).

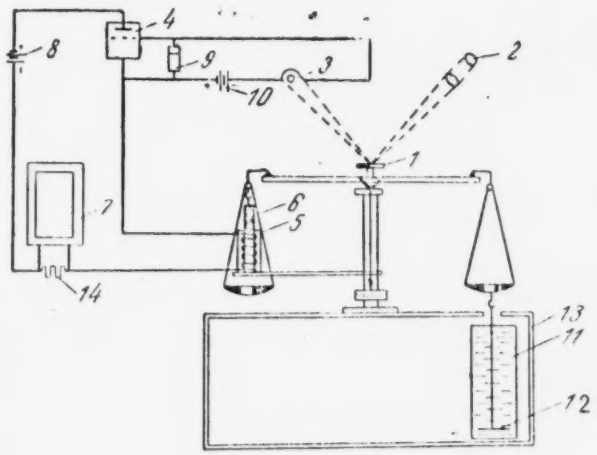

Fig. 11-3. Diagram of liquid sedimentograph with automatic weighing.

When the balance is at equilibrium, the beam from the illuminator strikes the mirror and, upon reflection, enters the photocell. The photoelectric current thus generated blanks the electron tube, so that there is no current in the anode circuit of the tube, and the recording instrument indicates zero. If the weight on the balance pan increases as a result of the settling of dust, the balance will go out of equilibrium, the beam from the illuminator will strike the blackened surface of the mirror, and the photoelectric cell will not be illuminated. As a result, the electron tube will be triggered, a current will be generated in the anode circuit, the solenoid interacting with the permanent magnet will not allow any observable deflection of the pan, and the balance needle will remain stationary. The magnitude of the anode current balancing the given weight will be shown by the recording instrument: this current will be proportional to the weight being measured on the balance pan.

Elements of the circuit which have not been mentioned are: 9 - anode resistance; 13 - cabinet; 14 - resistance controlling the scale range of the recorder.

The order in which the results from the settling curve are processed is no different from the one described above. The instrument is being successfully used at the NIIOGAZ and its branches.

Microscopic Analysis

The optical microscope may be used for determining the particle size in

the range from 1 to 30μ . The operating rules for microscopes have been thoroughly treated in special handbooks and are briefly described in the instruction manuals supplied with the instruments. We shall therefore consider chiefly the methods of preparation of specimens and particle size determination.

Preparation of specimens. At a dust concentration up to 1 g/m^3 and gas temperature up to 80°C, the sample for microscopic analysis may be withdrawn directly from the gas conduit by means of a sampling tube (Fig. 11-4), which contains a nitrocellulose membrane filter (GOST 8985-59) or an AFA-V-18-type filter. After the sample is withdrawn, these filters are transformed by clarifying in acetone vapors into a thin, texture-free transparent film on which the deposited particles are counted according to size under a microscope in transmitted light. The temperature restriction is due to the thermal stability of the filters, and the weight concentration restriction, to the difficulties involved in the isokinetic withdrawal of a sample containing a number of particles which are convenient for counting. A convenient amount of withdrawn dust is one in which there are about 500 particles in the field of view of the microscope. The volume of collected gas required to satisfy this condition is determined experimentally.

The rate of withdrawal of the sample by means of a tube of illustrated design should not exceed 10-15 l/min for reasons of the mechanical strength of the filters and moderate hydraulic resistance. At a dust concentration approaching 1 g/m^3, it is desirable to have a slow rate of sample withdrawal so that a number of particles convenient for counting can settle on the filters within a time interval that can be controlled. In order to observe the isokinetic conditions at different gas and sample withdrawal velocities, the tube is provided with interchangeable tips of different diameters.

The membrane filters consist of circular plates 35 mm in diameter and 0.1 ± 0.02 mm thick, made of porous nitrocellulose film. Depending on the pore size, the membrane filters are subdivided into six numbers: 1, 2, 3, 4, 5 and 6. The maximum size for the first five numbers is 0.6, 0.7, 0.9, 1.2, and 1.8 μ respectively. For filters No. 6, the maximum pore size is not regulated by GOST 8985-59. The membrane filters are produced by the Experimental Ultrafilter Plant at Mytishchi, Moscow Province.

The dependence of the hydraulic resistance of the membrane filters on the air flow rate is illustrated in Fig. 11-5. In order to obtain an acceptable hydraulic resistance during the withdrawal of the sample, filters No. 4 and 5 are usually employed. Filters No. 6 may yield a film of inhomogeneous thickness on clearing, thus complicating the counting of particles.

The AFA-V-18 filters consist of filters as such and protective paper rings (Fig. 11-6). The filtering material used is FPP-15 cloth. Each filter is placed in a separate envelope of tracing paper. The sets of filters are wrapped in a paper ring, ten filters per ring.

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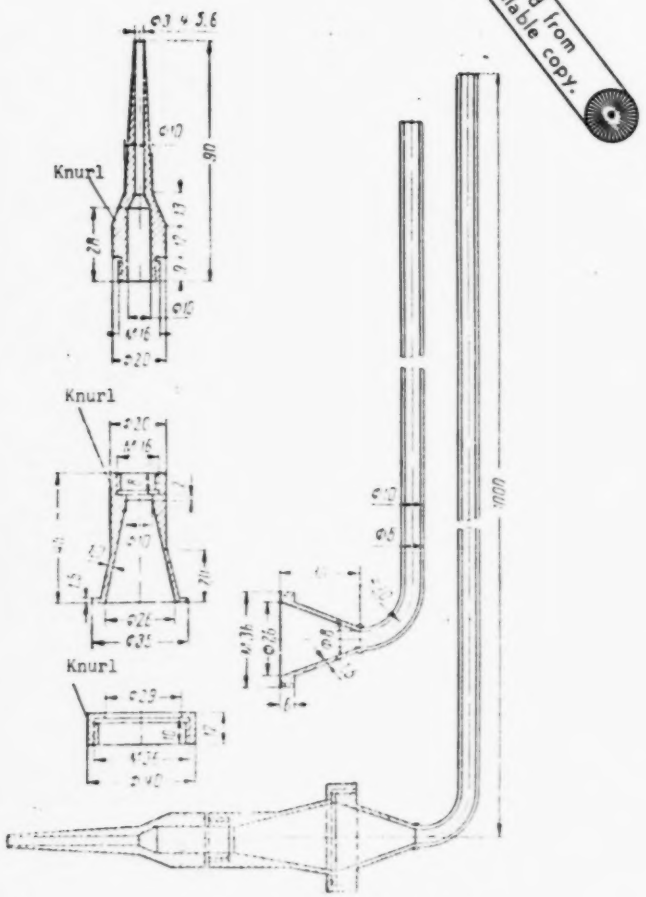


Fig. 11-4. NIIOGAZ tube for collection of samples on membrane filters.

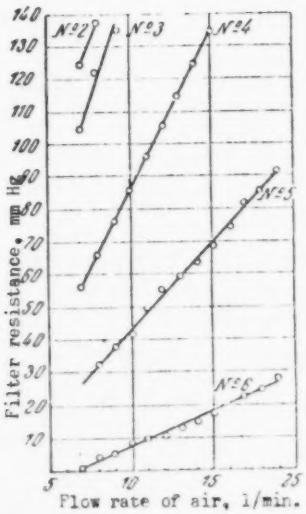


Fig. 11-5. Hydraulic resistance of membrane filters versus air flow rate.

Measurements made at NIIOGAZ by V. S. Morozov and I. F. Ryabinkin with a 26 mm diameter of working area of the filter.

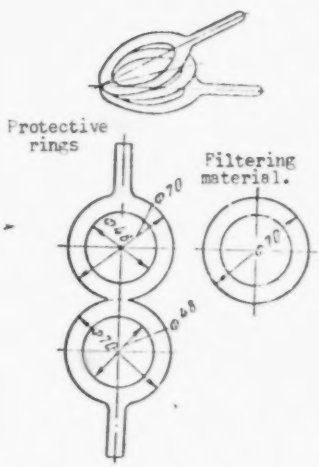


Fig. 11-6. AFA-V-18 type filters.

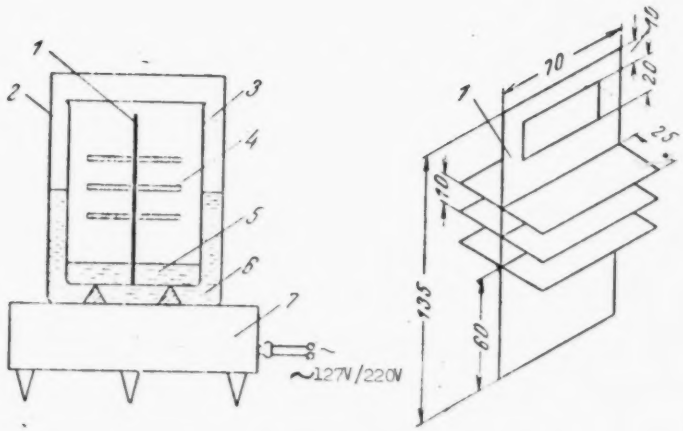


Fig. 11-7. Arrangement for clarifying membrane filters and AFA-V-18 filters.

1 - stand; 2 - beaker; 3 - beaker; 4 - microscope slide; 5 - acetone; 6 - water; 7 - electric hot plate.

When the sampling tube illustrated in Fig. 11-4 is used, a circle 35 mm in diameter is cut out of the AFA-V-18 filter. Protective rings of corresponding size are cut out of the tracing paper.

The AFA-V-18 filters have a much lower hydraulic resistance than membrane filters, but owing to the greater thickness and fine fibrous structure of these filters, the dust particles may penetrate to a certain depth relative to the surface and come to rest in more than one plane. At considerable magnifications, this complicates the focusing of the microscope to some extent.

Membrane filters and AFA-V-18 type filters are practically absolute filters. Analysis of the filtration mechanism has demonstrated, for example, that a membrane filter can hold particles about 10-15 times smaller than the average pore size [72].

The clarification of the filters in acetone pores may be carried out as follows.

Filters with samples for the determination of the size composition are sent to a laboratory and placed on microscope slides. The hanging edges are cut off. AFA-V-18 filters are placed on the slides so that the dust particles are located between the filter and the slide, and the membrane filters are placed in such a way that the dust particles are located on the top. The slides are marked in India ink with the number of the sample and date of its collection.

Water is then poured into a metal, porcelain or glass beaker 2 (Fig. 11-7), and a second beaker 3 of smaller size containing a small amount of acetone is placed inside the first beaker. The water in the beaker is heated on a hot plate to approximately 60°C. While the water is heated, the beaker containing acetone should be covered to prevent the acetone vapor from escaping. It is best to work under a hood.

Slides 4 with the filters are then laid on metal support 1, and the latter is placed in the beaker with acetone. Acted upon by the acetone vapors, the filters change into a transparent film. The time necessary for clarification of the filters depends on the water temperature. When the latter is 60°C, the filters clarify within a few minutes.

Very good specimens for microscopic analysis with membrane filters may be obtained by means of the attachment designed at the NIIOGAZ, shown in Fig. 11-8.

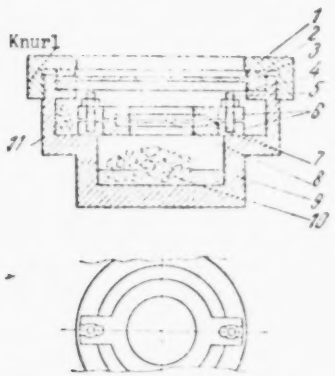


Fig. 11-8. Airtight beaker for clarifying membrane filters, designed by V. S. Morozov and I. F. Ryabinkin.

1 - lid; 2 - gasket; 3 - glass; 4 - gasket; 5 - clamping bolt with nut; 6 - upper and lower grip rings; 7 - ebonite rings; 8 - membrane filter; 9 - body of beaker; 10 - cotton wad wetted with acetone; 11 - cotton wad wetted with etner.

When this apparatus is used, the clarification is done as follows:

1. The lower grip ring 6 is placed on the table. Ebonite ring 7 is inserted into the cavity of this ring. A membrane filter is placed on the ebonite ring with its dust-covered side up, and is covered by the second ebonite ring and the upper grip ring. The grip rings are tightened with pins 5.

2. Cotton wad 10 is placed on the bottom of the beaker and soaked with 4-5 ml of acetone. Cotton wad 11 is placed on a special shelf inside the body of the beaker and soaked with ~ 1 ml of ethyl ether.

3. The clamp with the filter is placed in the beaker, which is covered with glass 3 and lid 1. A seal is made by means of rubber gaskets 4.

The clarification of the filter takes place in 20-30 min. The filter is considered clarified if one can easily read through it.

4. After the filter has been completely clarified, the lid is opened, and the ring clamp is taken out. The filter in the clamp must be held over the beaker for a while so as to allow the filter to dry gradually. Rapid drying might cause the filter to cloud.

5. The filter in the clamp is placed under a crystallizer for another 10-15 min of final drying.

6. If after drying the filters are pulled out of the rings, the ebonite rings should be lightly coated with glue 88 or BF-2 before starting the clarification.

7. After drying, the filter together with the ebonite rings is taken out of the clamp and placed on the microscope slide.

At a dust concentration in the gases of 1 g/m^3 or a high gas temperature, the method of microscopy is usually employed for the determination of the original particle size only. To this end, the dust sample collected by means of a paper or cloth filter is introduced into a beaker with distilled water and thoroughly stirred with a glass rod. To peptize the fine particles, one or two drops of a suitable peptizer (frequently ammonia) is added, the sample is stirred again, a few drops are transferred by a pipette to a microscope slide, and the drops are spread over the slide with the pipette. The water is allowed to evaporate. When the specimen obtained is examined under the miscroscope, one should make sure that the dust particles do not overlap or adhere to one another; otherwise, a new sample of greater dilution or with a different peptizer must be prepared.

Determination of particle sizes. The sizes of the particles magnified by the microscope are measured with objective and ocular micrometers, the usual assumption being that the particles are spherical in shape. The method of "constant directions," i. e., the determination of the size of all particles along a certain axis (Fig. 11-9), is the most convenient for finding the particle size distribution.

With dusts whose particles do not differ appreciably in size, it is sufficient to measure approximately 500 particles; if the polydispersity is substantial, several thousand particles should be measured.

The counting of dust particles in the microscope is a laborious and painstaking process. The work is considerably facilitated and more accurate results are obtained if the image of the particles is photographed with a photographic microscope attachment, and the counting is done on magnified photographic prints or projections of the negatives on sheets of white paper placed under the photographic enlarger. The object micrometer is photographed together with the specimen of dust studied. This makes it easier to determine the scale of the dust image obtained by means of the enlarger.

In determining the distribution of the dust particles according to the sizes of their images on the photographic print or screen of the enlarger, it is convenient to use templates. In this case, the area of dust particles of irregular shape is compared to the area of circles drawn on the template on the corresponding scale.

Fig. 11-9. Measurement of dust particle size by the constant direction method.

Counting the number of particles with sizes in a certain interval (fractions), gives the so-called calculated distribution. In order to convert the distribution of particles according to fractions into units of weight, it is necessary to know the average size (diameters) for each fraction. They can be determined by designating as d_a and d_b the extreme sizes of the particles of a fraction, using the following relation:

$$d_{av} = \sqrt{\frac{d_a^3 + d_b^3}{2}}. \qquad (11\text{-}4)$$

By using the equality between the weight ratios of the dust particles in each of the fractions and the volume that they occupy, one can find the weight percentage of each fraction

$$\frac{d_{avk}^3 n_k \cdot 100}{\sum_1^i d_{av}^3 n}, \ \% \qquad (11\text{-}5)$$

Here d_{av} is the average particle size of the fraction;

n is the percent content of particles comprising the fraction;

k is the number of the fraction;

i is the number of fractions into which the analyzed dust is subdivided.

Method of Three Cyclones*

This method of determination of dust dispersity is based on the assumption that the distribution studied obeys the lognormal law. With this condition, the determination of the size composition of dust can be made if the following two parameters are known: the average gravimetric geometric diameter $\overline{d}_{geom}$ and the dispersion of the distribution, in place of which it is more convenient to use the quantity ξ, i. e., the gravimetric content of particles with a diameter of less than $2\overline{d}_{geom}$ (see § 1-1).

The instrument for the determination of dust dispersity by this method consists of three successively mounted cyclones and a glass wool filter (Fig. 11-10). Teflon or aluminum beakers are placed inside each cyclone. Before the sample is taken, the beaker and the filter are weighed.

*The theory underlying the method has been treated in detail by S. S. Yankovskiy and N. A. Fuks [74].

When a sample of dust-laden gas is taken, the instrument is introduced into the gas conduit through a port with a useful cross section of 220 x 80 mm, so that the tip of the inlet tube of the first cyclone is parallel to the axis of the gas conduit. The port cover should have a connecting pipe for the introduction of the suction tube from the outside.

When the gas temperature is high, prior to the collection of the sample, the instrument is kept in the gas conduit for a while in order to warm it up and thus exclude the condensation of moisture inside it. The suction tube should be kept open during that time. Because of the rarefaction in the gas conduit, a slight air current through the tip of the instrument is thus established, which prevents dust from entering th instrument during the warm-up. The tip of the instrument during the heating is turned to coincide with the direction of gas flow.

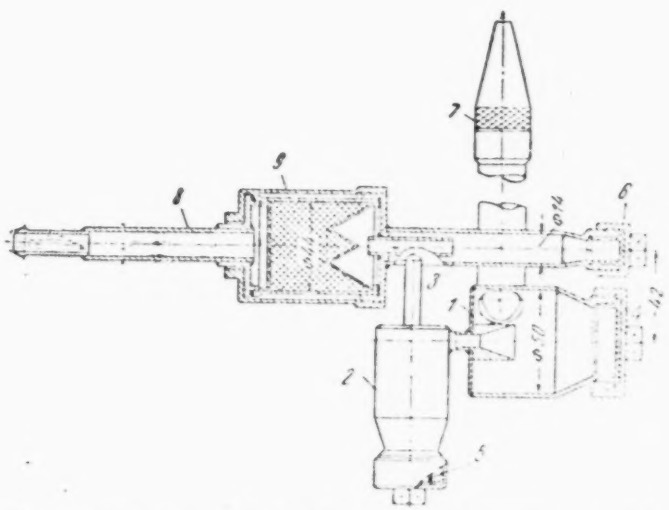


Fig. 11-10. Instrument for determining the dispersity composition of dust by the method of three cyclones.

1, 2, 3 - cyclones; 4, 5, 6 - beakers; 7 - interchangeable tip; 8 - tube for sucking the gas through the instrument; 9 - glass wool filter.

The diameter of the tip is chosen so that the isokinetic condition is fulfilled at a sample collection rate of 10 l/min.

After heating, the instrument is turned with its tip against the flow, and a certain amount of gas containing from one to several grams of dust is sucked in through the instrument at the rate of 10 l/min. The instrument is then removed from the gas conduit, the dust clinging to it on the outside is wiped off, and the beakers containing the settled dust and the glass wool filter are taken out. By weighing the beakers and filter for the second time, one finds the weight of dust settled therin, g_1, g_2, g_3, and g_f. The average

gravimetric geometric diameter $\bar{d}_{geom}$ and ξ, the gravimetric content of particles with diameters less than $2\bar{d}_{geom}$, which characterize the unknown distribution, may be determined by means of the nomograms illustrated in Fig. 11-11. In order to use the nomograms it is necessary to calculate the breakthroughs of the dust through each of the cyclones, ε_1, ε_2 and ε_3:

$$\left.\begin{aligned} \varepsilon_1 &= \frac{g_2 + g_3 + gf}{g_1 + g_2 + g_3 + gf}; \\ \varepsilon_2 &= \frac{g_3 + gf}{g_1 + g_2 + g_3 + gf}; \\ \varepsilon_3 &= \frac{gf}{g_1 + g_2 + g_3 + gf}. \end{aligned}\right\} \qquad (11\text{-}6)$$

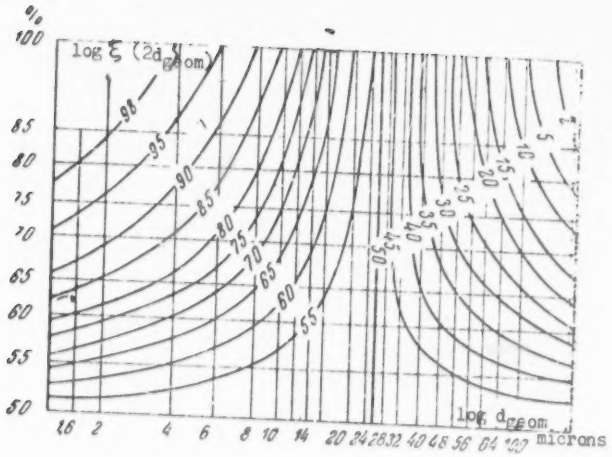
The nomograms show curves of equal breakthroughs through each of the cyclones for dusts with different values of $\bar{d}_{geom}$ and ξ.

To find the unknown distribution on the basis of the experimentally obtained values of the breakthrough for the three cyclones, the following procedure should be used. A tracing paper with coordinate axes is placed on each of the three nomograms successively, and the three curves corresponding to the calculated values of ε_1, ε_2 and ε_3 are traced on it. If the particle size distribution of the dust studied is strictly lognormal and there are no experimental errors, these curves should intersect at a single point whose abscissa corresponds to the unknown value $\bar{d}_{geom}$ and the ordinate to the value of ξ.

Actually, because of measurement inaccuracies and deviations from the lognormal distribution, the curves form a triangle whose center gives the best approximation to the values of $\bar{d}_{geom}$ and ξ of the size composition being sought.

The nomograms were constructed for particles of unit density. If it is desired to express the distribution over sizes of particles with density ρ_d different from unity, the value of $\bar{d}_{geom}$ found must be divided by $\sqrt{\rho_d}$. When the sample is collected from a gas at a high temperature, the value of $\bar{d}_{geom}$ found must be multiplied by $\sqrt{\mu_t/\mu_0}$, where μ_t is the viscosity of the gas at the temperature of the gas conduit; μ_0 is the viscosity of air at room temperature (at which the calibration of the cyclones was carried out). Knowing $\bar{d}_{geom}$ and ξ for the dust studied, one can plot the particle size distribution on logarithmic probability paper (Fig. 1-1d)* in the form of a straight line passing through two points.

* Editor's note: This figure can be found in the paper "General Aspects of the Design and Operation of Gas Purification Systems" in this report.



a)

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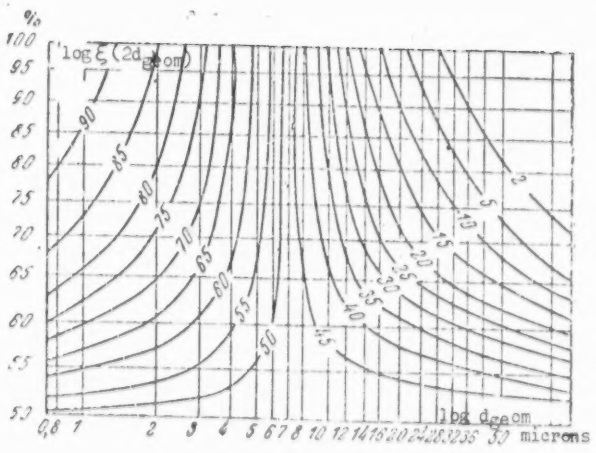

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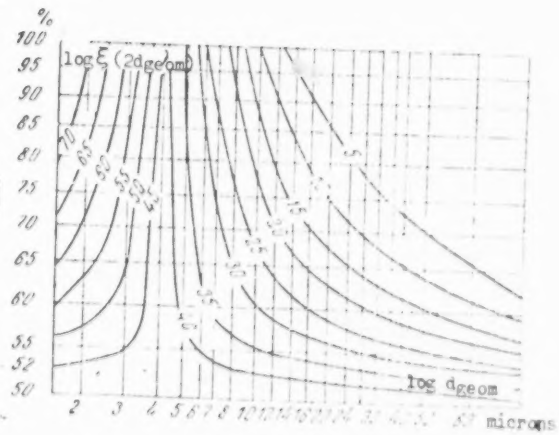

c)

Fig. 11-11. Nomogram for determining d_2 and ξ.

a - for first cyclone; b - for second cyclone; c - for third cyclone.

The first point is obtained by marking the value of $\overline{d}_{geom}$ on the abscissa axis. To the right of this point on the same axis, a point corresponding to $2\overline{d}_{geom}$ is marked on the same axis, then a perpendicular at this point is raised on which the value of ξ is marked in percent; the second point is thus determined.

An accuracy of the results obtained with the instrument, acceptable for the solution of practical problems, is obtained in this case if the average geometric size of the particles of the dust under analysis falls within an interval of approximately 25 to 2μ . This is because particles larger than 25μ are equally trapped in the first cyclone regardless of the size, whereas those measuring approximately 1.5 microns practically are not trapped by the cyclones and fly directly into the filter. If after the sample has been collected it is found that almost all of the dust has settled in the first cyclone, the dust in this cyclone should be subjected to a supplementary analysis in an air separator. The accuracy of the analysis made by the air separation method will be very high because of the absence of fine fractions. Then, knowing the size composition and weight fraction of the additionally analyzed dust, one can readily plot a general distribution curve with much greater accuracy than if all of the dust had been directly analyzed in the gas separator.

The instrument is manufactured by interested organizations according to the NIIOGAZ design.

Multistage Jet Settler

In a multistage jet settler, known abroad under the name of "cascade impactor," use is made of inertial settling of the dust particles caused by the flow around a flat obstacle by a jet of dust-laden gas. The gas jet passes through several successive nozzles at a progressively increasing velocity, and the dust particles settle and are held on surfaces coated with a layer of adhesive lubricant. The presence of a correlation between the size of the settling particles and the gas velocity allows one to evaluate the dispersity of the dust by estimating the proportion of particles settled on the surface opposite each of the nozzles. The principle of inertial settling employed pertains to the number of dust particles ensuring the best separation into fractions. Earlier, jet settlers have been used chiefly for the hygienic evaluation of the contamination of atmospheric air and were unsuitable for practical size analysis of industrial dusts because adhesive lubricants proved capable of holding reliably only monolayers of the settling particles. Such small dust samples, first, are impossible to withdraw from the gas conduits while observing the isokinetic condition (for dust contents of gases typical of industrial discharges) and second, were impossible to analyze by the most convenient method of weighing of deposits obtained at different stages of the apparatus.

At the same time, the simplicity of design, speed of analysis and fundamental possibility of achieving accurate results made the use of jet settlers highly promising for the analysis of industrial dusts when the instrument was placed inside gas conduits. In this connection, the NIIOGAZ selected a lubricant composition* ensuring the accumulation at each stage of the instrument of up to 30-40 mg of analyzed particles, and a suitable design of the instrument was developed.

The instrument (Fig. 11-12) consists of eight stages, seven of which are designed for the inertial settling of analyzed dust particles and the eight for settling by the filtration method. Each of the stages of inertial settling consists of a beaker which includes a nozzle opposite which is mounted a tray filled with a special lubricant. Each tray edge has one notch which makes it possible to mount the trays between suitable pins, as shown in the figure. The filter of the eighth stage is filled with glass wool. The first stage of the instrument is equipped with a removable tip, which permits an isokinetic collection of the sample at different velocities of the gas stream while the rate of gas flow through the instrument chosen during the calibration is retained. All the stages of the jet settler are combined in a cylindrical housing. Packing between the stages consists of teflon gaskets tightened by the lid of the housing. An additional tightening of the gaskets is achieved by means of three expansion stay bolts attached to the lid.

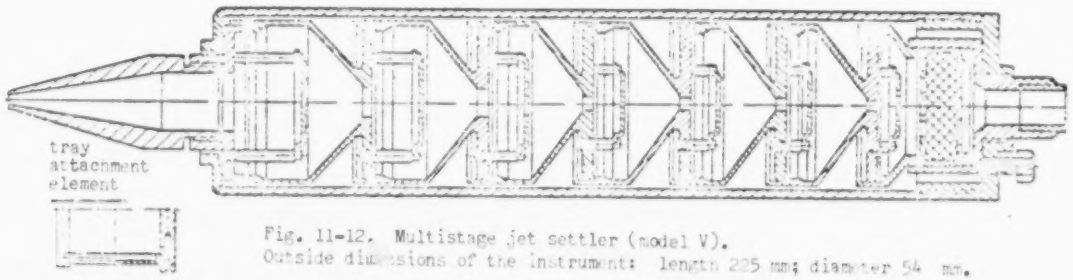

Fig. 11-12. Multistage jet settler (model V).
Outside dimensions of the instrument: length 225 mm; diameter 54 mm.

The lubricant for holding the particles on the surface of the trays is a mixture consisting of a solid and a liquid phase. The solid phase gives it the thickness required to prevent it from splashing when acted upon by the gas jet, whose velocity at the exit from the last nozzle may be as high as 100 m/sec. The liquid phase holds on to the particles which settle on the surface by wetting them, owing to the diffusion from the lubricant layer into the growing dust layer. Since the diffusion rate must be slightly higher than the growth rate of the layer, the applicability of the instrument is limited by a weight concentration of the dust in the gases of up to 1-7 g/m^3, depending on the bulk density of the dust being analyzed.

*S. S. Yankovskiy and A. A. Rusanov, USSR Authorship Certificate No. 197844.

Composition of Lubricant at Gas Temperatures up to 80°C

Vaseline oil	2 parts
Gas black	1 part
At gas temperatures from 80 to 150°C	
MS-20 oil	1 part
M-14 corundum	3.5 parts

Several modifications of the instrument have been developed which differ mainly in the number of stages, configuration, and nozzle diameter. The characteristics of the individual stages were determined by the method of microscopic analysis of the particles settling in them, at a flow rate of the gases through the instruments of 10 l/min. This gas flow rate, specified during the construction, was chosen for the following reasons: at high flow rates, the outside dimensions of the instrument increase; at lower ones, the entrance diameter of the tip required for an isokinetic collection of the sample will be too small and will start to plug up with the dust. The limiting sizes of particles of unit density for each fraction settling on the stages of the instrument shown in Fig. 11-12 are listed in Table 11-1 (the values are rounded off slightly).

The determination of the dust dispersity by means of a jet settler amounts to the following. The instrument with the weighed trays full of lubricant and with the filter is placed in the gas conduit in such a way that the direction of the nozzle coincides with the direction of motion of the gases. After it is heated up to the temperature of the gases, the jet settler is turned by 180° so that the nozzle faces in the direction opposite to that of the flow, and a certain amount of the gases is drawn off through the nozzle by means of a gas blower or other source of suction at a velocity chosen during the calibration.

Table 11-1.

Number of Stage	Diameter of Nozzle, mm	Limiting Particle Size, Microns, at ρ_d=.1 g/cm³,
I	20	> 42,5
II	14	24,5
III	10	15,0
IV	7	8,5
V	5	5,2
VI	3,5	3,2
VII	2,0	1,4
VIII	Filter.	<1,4

The instrument is then removed from the gas conduit, and the filter and trays are weighed on an analytical balance.

The plotting of the size composition curve from the experimentally obtained weight increases of the dust in the cups of the various stages and on the filter is carried out as follows.

The relative fraction f_1 of particles settled on the first stage is found as the ratio

$$f_1 = \frac{g_1}{g_1 + g_2 + g_3 + g_4 + g_5 + g_6 + g_7 + g_f}, \qquad (11\text{-}7)$$

where g_1, g_2, g_3, g_4, g_5, g_6, and g_7 are the weight increases of the first, second, third, fourth, fifth, sixth, and seventh stages, and g_f is the weight increase of the filter. The fraction of particles settled on the first and second stages is found as the ratio $f_2 = (g_1+g_2)/(g_1+g_2+g_3+g_4+g_5+g_6+g_7+g_f)$. The fractions f_3, f_4, ..., f_8 of particles settled on the following stages are found in similar fashion.

Values of the relative amounts of settled particles f_1, f_2, f_3, f_4, f_5, f_6 and f_7 are laid off as the ordinates of points with abscissas corresponding to the separation limits d_1, d_2, d_3, d_4, d_5, d_6 and d_7 (for which the values given in Table 11-1 can be taken) in the logarithmic probability coordinate system (Fig. 1-1d).

At high gas temperatures, the initial weight of lubricant begins to decrease owing to the evaporation of the oil and to desorption processes. The weight lost by desorption is restored partly or fully after a certain time, but the weight lost through the evaporation of oil is not. The character of the weight loss of the lubricant for trays filled to the brim and weighed a day after the heating is shown in Fig. 11-13. This loss should be taken into account during weighing. The weight loss of the lubricant can be taken into account most accurately as follows. After the dust sample has been collected for analysis, trays with fresh lubricant should be placed in the jet settler, and, after protecting the dust-collecting tip with a filter of conventional design, suction of the gases should be carried out during the same interval of time during which the dust sample was collected. The averaged weight losses of the three trays 30 mm in diameter and four trays 23 mm in diameter will give close-to-true corrections, which should be introduced into the calculations.

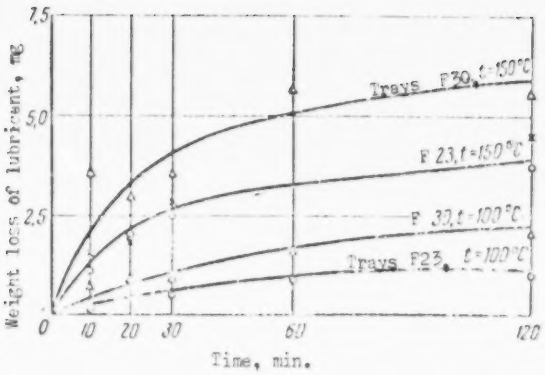

Fig. 11-13. Weight loss of the lubricant (1 g of MS-20 oil plus 3.2 parts of M14 corundum).

The instrument is manufactured by interested organizations according to NIIOGAZ blueprints.

11-2. Measurement of the Electrical Resistivity of Dust Under Industrial Conditions

At the present time, it is not possible to determine the electrical resistivity (ER) of dust directly on the collecting electrodes of electrostatic precipitators. Therefore, it is usually necessary to resort to the measurement of the ER of dust (under both laboratory and industrial conditions) between special measuring electrodes. Most frequently, a layer of dust is formed on one of the electrodes in one way or another, and the second measuring electrode is applied on the already-formed dust layer.

The absolute values of the measured quantities are of course strongly dependent on the method of formation of the dust layer and the method of measurement.

In selecting the optimum type, size and operating parameters of electrostatic precipitators, it is necessary to have information on the ER values of different dusts for the parameters of dust-laden gas streams which the latter have at the entrance to the apparatus.

In order to adopt a single method permitting a comparison of the results obtained, the NIIOGAZ has designed an instrument called the "Tsiklonom-1" [85], which meets the following requirements: simplicity of design and handling; good reproducibility of the results; ability to measure the ER of dust in streams of process gases.

The instrument permits the measurement of the ER of dusts in the 20-250°C temperature range.

The instrument consists of a small-sized high-efficiency cyclone and a dust resistivity gauge located in its hopper. The measuring system of the gauge consists of cylindrical coaxial electrodes (Fig. 11-14).

The dust-laden gas stream enters through the intake tube into the cyclone, in which the dust is separated from the gas. The gas is then expelled through the exhaust part of the cyclone, while the dust is poured into the hopper and fills the interelectrode gap of the gauge.

The housing of the gauge is made of teflon, which has a high volume resistivity, 10^{17} ohm cm at 20°C, and a high surface resistivity, 10^{16} ohm.

The measuring system is connected to a secondary indicator, a teraohmmeter, by a wire with a heat-resistant organosilicon insulation of brand PTL-250.

To prevent the contamination of the measuring wires with dust and their vibration during the flow of the gas around the instrument, the latter is provided with a protective metallic jacket.

"Tsiklonom-1" is fastened by three hollow metal bolts to the flange on which the instrument is mounted in the gas conduit. The connecting wires extend out of the gas conduit through two of the bolts, and a thermometer or thermocouple can be inserted through the third to check the temperature of the medium in the immediate vicinity of the gauge.

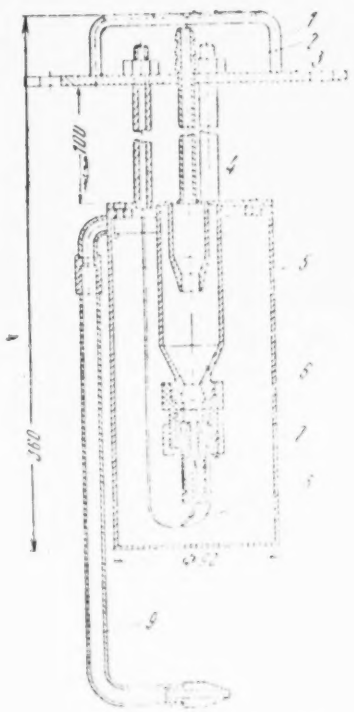

Fig. 11-14. Instrument for measuring the electrical resistivity of a dust layer by means of "Tsiklonom-1".

1 - handle; 2 - nut; 3 - flange; 4 - bolt; 5 - cyclone; 6 - gauge; 7 - protective jacket; 8 - measuring wires; 9 - intake tube.

In a possible variant of the arrangement, the thermocouple is placed directly in the measuring system of the gauge.

The design of the instrument makes it possible to: form in the interelectrode gap a dust layer by a method excluding subjective errors due to the distortion of the layer during measurement of the ER by the method of application of the electrode on the layer; measure the electrical resistivity of

the dust layer formed directly in the gas conduit over a wide temperature range and in chemically corrosive media; check the temperature of the gas stream and hence of the dust layer directly in the zone of the gauge; automatically record the ER of dust on a recording instrument, and read off the ER directly on the secondary instrument thanks to a suitable choice of the geometry of the measuring electrodes.

The operational sequence with the "Tsiklonom-1" instrument is as follows.

Before the instrument is introduced into the gas conduit, the insulation level of the measuring system of the gauge is determined, then the instrument is inserted into the gas conduit and warmed up for 10-15 min. After the warm-up, the insulation level of the measuring system is checked again. The instrument is connected to a vacuum line, and the gas flow rate is set at 15-25 l/min. The optimum efficiency and hydraulic resistance of the instrument are thus established.

It was found experimentally that a slight distortion of the size composition of the sample collected in the instrument, caused by a deviation from isokinetic withdrawal, did not cuase an appreciable change in the ER of dust.

To prevent stoppage of the vacuum source with dust that has not been trapped by the cyclone, it is recommended that a paper filter be installed in the suction line.

The time required for filling the measuring system with dust is determined experimentally. Tests of the instrument under industrial conditions showed that at a gas flow rate of the order of 20 l/min and a dust content of the dust-laden gas stream of 5-7 g/m^3, the time necessary for filling the hopper ranged from 15 to 20 min.

When the withdrawal of the gas is complete, the connecting wires are attached to the secondary instrument and the electrical resistivity of the dust layer between the electrodes of the gauge is determined. To determine the ER of the layer on measuring electrodes in the form of coaxial cylinders, the following expression is used:

$$\rho = \frac{2\pi HR}{\ln \frac{r_2}{r_1}}, \qquad (11\text{-}8)$$

where ρ is the electrical resistivity of the dust, ohm cm;
R is the resistance, measured with a teraohmmeter, ohm;
H is the height of the measuring electrode, cm;
r_1 and r_2 are the radii of the inner and the outer electrode, cm.

Thanks to a specially chosen electrode geometry, $\rho = 10\ R$ (ohm cm), i. e., the need for any computations is eliminated.

The secondary instrument for measuring the resistance of the dust layer, the teraohmmeter, measures the total resistance (R_{tot}) of the gauge insulation (R_{in}) and the resistance of the dust layer proper (R_x), connected in parallel. If the resistance measured by the teraohmmeter $R_{tot} \leq 0.01\ R_{in}$, it may be assumed with an error of not more than 10% that $R_x = R_{tot}$. In other cases, the resistance of the dust layer must be calculated from the formula

$$R_x = \frac{R_{tot} R_{in}}{R_{in} - R_{tot}} \qquad (11\text{-}9)$$

Therefore, in working with the "Tsiklonom-1" instrument, prior to each experiment it is necessary to check the insulation resistance level of this gauge. The instrument is manufactured by interested organizations from blueprints of the NIIOGAZ institute.

11-3. Determination of the Moisture Content and Dew Point of Gases

A large number of methods have been developed for the determination of the moisture content of gases. In Chapter 1 it was pointed out that data on the moisture content of gases are necessary chiefly in order to avoid the cooling of gases in the lines of dust-collecting systems below the dew point, which depends on the moisture content.

The moisture content of gases that do not contain impurities that raise the dew point is most frequently determined by means of psychrometers or by the condensation method. If the gas contains impurities (for example, SO_3), susceptible of substantially raising the temperature of the start of condensation, i. e., the dew point, the latter is determined by using instruments based on the principle of measuring the temperature of the cooled surface at the instant of formation of the dew on it.

1. Determination of the moisture content of gases by means of a psychrometer. The psychrometric method of determining the moisture content of gases is based on the difference between the temperature readings of a dry and a wet thermometer. The dry thermometer indicates the temperature of the surrounding unsaturated gas, whereas the wet thermometer placed in the same medium shows a lower temperature, since water evaporates from its surface and thus consumes heat. The equilibrium temperature assumed by the surface of the water evaporating under adiabatic conditions (when the amount of heat transferred from the gas to the liquid is equal to the latent heat of vaporization) is referred to as the wet thermometer temperature. The lower the partial pressure of the

water vapor in the gas bathing the termometers, the larger the difference between the readings of the dry and wet thermometers.

The pressure of water vapor under the conditions of a psychrometer is given by the formula

$$p^{H_2O}_{ps} = p^{H_2O}_{sat} - c(t_d - t_m) P_{ps} \qquad (11\text{-}10)$$

where $p^{H_2O}_{sat}$ is the pressure of saturated water vapor at the wet thermometer temperature, mm Hg (taken from saturated water vapor tables);

t_d is the dry thermometer temperature, °C;

t_m is the wet thermometer temperature, °C;

P_{ps} is the pressure in the psychrometer, mm Hg;

c is a coefficient which depends on the velocity of the air (gas) around the bulb of the wet thermometer. At a gas velocity of over 5 m/sec, c may be taken as 0.00066.

The pressure of water vapor in the gas conduit is calculated from the formula

$$p^{H_2O}_{g} = \frac{p^{H_2O}_{ps} P_g}{P_{ps}}, \qquad (11\text{-}11)$$

where P_g is the pressure in the gas conduit, mm Hg

Knowing the water vapor tension in the gas conduit, one can determine the dew point and absolute humidity of the gas from tables [71].

A large number of different versions of psychrometers have been proposed whose main differences lie only in the details and material of which they are made. We shall discuss an NIIOGAZ-designed psychrometer, which because of its simplicity of design may be made in any glassblowing shop [70].

The psychrometer under consideration is in the form of a U-shaped vessel into which two T-joints are inserted (Fig. 11-15). One of the T-joints (for the dry thermometer) is bent in the shape of the vessel, and the other (for the wet thermometer) has the usual straight shape. Two thermometers with a scale from 0 to 50° (Assman psychrometric thermometers) or from 30 to 100° (thermometers for Zhukov's instrument) are placed in the T-joints in rubber stoppers. A scale division of such thermometers is equivalent to 0.2°C.

Before the installation in the instrument, the thermometer readings should be thoroughly compared with one another.

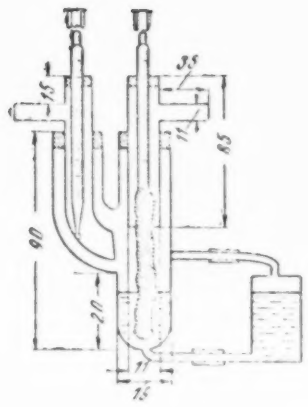

Fig. 11-15. Psychrometer

The dry thermometer is lowered down to the elbow of the T-joint and the "bulb" forming its bottom comes to rest against the wall of the elbow. The wet thermometer is inserted in the second (straight) T-joint exactly in its center, so that the end of the mercury bulb is located at the same level as the end of the T-joint.

The bulb of the wet thermometer is wrapped in gauze so that its lower end reaches the bottom of the vessel, and the upper end protrudes 5 mm beyond the limit of the upper part of the mercury bulb of the thermometer. The water supply to the psychrometer is regulated by means of an equalizing flask.

The assembled instrument is placed in a wooden case lined with a heat-insulating material.

The gas from which dust has been filtered off and whose temperature is above the dew point is drawn through the psychrometer, bathing the thermometer bulbs, first the dry one and then the wet one. In calculating the necessary amount of gas drawn through (in order to maintain the necessary velocity of the gas flow around the bulb of the wet thermometer), the inner diameter of the T-joint and the diameter of the bulb of the thermometer wrapped in gauze are measured. From the cross-sectional area of the T-joint one calculates the area occupied by the thermometer, and the volume velocity for this area is then calculated

$$Q = w(F - f)60 \cdot 10^3 \ \text{ℓ/min} \qquad (11\text{-}12)$$

where w is the linear velocity (≥ 5 m/sec) of the gas, m/sec;

F is the cross-sectional area of the T-joint, m^2;

f is the area occupied by the thermometer wrapped in gauze, m^2.

After the readings of the dry and wet thermometers have been established, these readings are recorded every 2-3 min for 20-30 min, and the results obtained are averaged out.

Determination of moisture content by the condensation method. In this method of moisture content determination, the gas, which is not saturated with water vapor, is cooled below the dew point, and the amount of collected, condensed moisture and the temperature of the cooled gas are measured.

The moisture content is defined as the sum, referred to a unit volume of the gas, of the condensed moisture and absolute moisture contents of the saturated gas.

One of the types of instruments for determining the moisture content by the condensation method is shown in Fig. 11-16. During the determination, no spray carry-over from the instrument and no condensation in the supply tubes must be allowed. The amount of gas (from which the dust was first separated by filtration) passed through the instrument is measured by means of a rheometer or other flow meter.

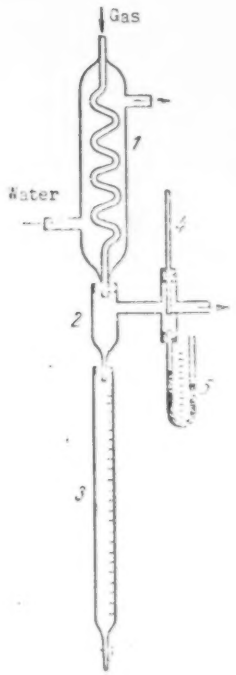

Fig. 11-16. Instrument for determining the humidity of gases by the condensation method.

1 - reflux condenser; 2 - moisture separator; 3 - burette for measuring the amount of collected condensate; 4 - thermometer; 5 - manometer.

For a more accurate determination of the moisture content of gases by this method, one can measure the amount of condensed water by a gravimetric instead of a volumetric method. In addition, a wool filter may be installed to block the spray and mist.

Determination of the moisture content of gases from observation of dew formation on a cooled surface. In a direct determination of the dew point, an instrument developed by the VTI and shown in Fig. 11-17 may be employed. The main element of this instrument is a measuring cap of molybdenum glass into the surface of which are fused two platinum electrodes separated by a distance of 7 mm. A voltage of 12 V is applied to these electrodes. A platinum/platinum-rhodium thermocouple is fused into the glass between them.

The instrument is mounted in the gas conduit at right angles to the motion of the gases or at a slight angle towards the stream, so that the cap is fully bathed by the gases and is not located in the aerodynamic shadow. After the warm-up of the instrument, the cooling air is supplied into the cap.

When the temperature of the cap falls below the dew point, a film of moisture that abruptly decreases the resistance of the segment between the electrodes appears on the surface of the cap. The changes of temperature and resistance are recorded. The graphical relations plotted on the basis of the measurements permit one to make an accurate evaluation of the dew point.

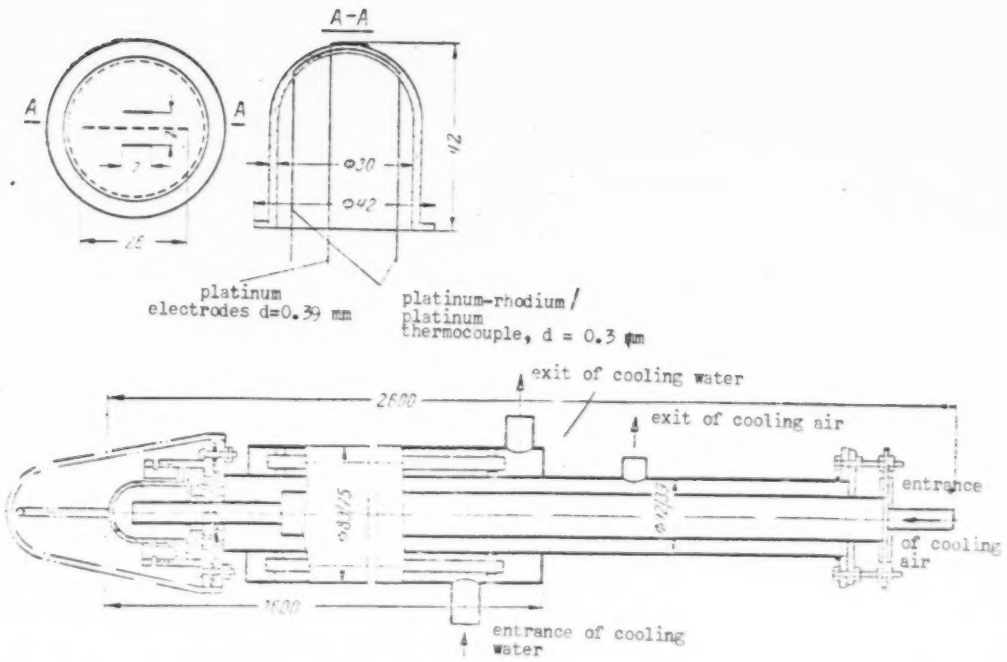

Fig. 11-17. VTI instrument for determining the dew point.

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